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Local retail food environment exposure and diet quality in rural and urban adults: A longitudinal analysis of the ORISCAV-LUX cohort study

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ABSTRACT

Despite growing interest in understanding how food environments shape dietary behaviors, European longitudinal evidence is scarce. We aimed to investigate the associations of 9-year average and change in exposure to local retail food environments with the diet quality of residents in Luxembourg. We used data from 566 adults enrolled in both waves of the nationwide ORISCAV-LUX study (2007–2017). Dietary quality was assessed by the Diet Quality Index-International (DQI-I). Exposure to “healthy” and “less healthy” food outlets was assessed by both absolute and relative GIS-based measurements. The results showed a 56.3% increase in less healthy food outlets over the period. In adjusted linear mixed models, high (vs. low) 9-year average exposure to less healthy food outlets was associated with lower DQI-I, when examining spatial access ($\beta = -1.25$, 95% CI: $-2.29, -0.22$) and proportions ($\beta = -1.24$, 95% CI: $-2.15, -0.33$). Stratified analyses showed these associations to be significant only among urban residents. There was no association between change in exposure to less healthy food outlets and DQI-I. Increased exposure to healthy outlets in rural areas, using absolute measurements, was associated with worsened DQI-I. Neighborhood socioeconomic status did not moderate the above associations. Findings suggest that the proliferation of less healthy food outlets may have contributed to the deterioration of the diet quality of urban residents, and support the use of relative measurements to fully capture the healthiness of food environments.

1. Introduction

Poor diet quality and nutrition are major preventable risk factors for overweight and obesity, as well as for non-communicable diet-related conditions, such as cardiovascular diseases, cancer, and diabetes (Afshin et al., 2019; GBD 2017 Risk Factor Collaborators, 2018; Clinton et al., 2020; Micha et al., 2017; Roth et al., 2020), which are the leading causes of death worldwide (GBD 2017 Risk Factor Collaborators, 2018). In the European region, the burden of disease associated with poor nutrition continues to grow (GBD 2017 Risk Factor Collaborators, 2018). Over the

past 40 years, the prevalence of overweight and obesity increased by half, affecting almost 60% of the adult European population (WHO Regional Office for Europe, 2022). The Global Burden of Disease Study also estimates that about 2.1 million cardiovascular deaths in the WHO European Region were attributable to unhealthy diets, particularly being low in whole grains, fruits and vegetables, nuts and seeds, and polyunsaturated fatty acids; and high in sodium (Meier et al., 2019), with important inequalities by socioeconomic background (WHO Regional Office for Europe, 2020). The Grand Duchy of Luxembourg is no exception. Despite the implementation of national dietary guidelines

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in 2006 (Luxembourg Ministry of Health, 2007), the population's diet quality continued to deteriorate between 2007 and 2017 (Vahid et al., 2021). In 2019, poor nutrition was estimated to account for about 13% of all deaths in Luxembourg (OECD/European Observatory on Health Systems, 2021).

The food environment, defined as “the collective physical, economic, policy and sociocultural surroundings” (Swinburn et al., 2013a), is today recognized as an important factor shaping population food choices and diet quality (Brug, 2008; Story et al., 2008). Specifically, neighborhood food environments (type, location, and number of food outlets), have been paid increasing attention in research and policy as a way to create healthy food environments (Swinburn et al., 2013b) by shaping the availability (density) and accessibility (proximity) of food outlets (Charreire et al., 2010). For example, greater residential availability of fast-food outlets has previously been linked to increased fast-food consumption (Athens et al., 2016; Bernsdorf et al., 2017; Boone-Heinonen et al., 2011a; Moore et al., 2009; Richardson et al., 2015; Dunn et al., 2012; Thornton et al., 2009; Sharkey et al., 2011) and poorer diet quality (Moore et al., 2009; Richardson et al., 2015; Rummo et al., 2017), while greater exposure to supermarkets has been associated with increased fruit and vegetable consumption (Clary et al., 2016; Pessoa et al., 2015; Thornton et al., 2012; Duran et al., 2016; Evans et al., 2012; Morland et al., 2002) and better diet quality (Moore et al., 2008). Yet, the food environment is often characterized by a complex interplay of fast-food restaurants, supermarkets and other food outlets. Therefore, there is a need to account for the relative presence of healthy and less healthy food outlets, rather than their absolute numbers alone, to better understand the overall effect of the local food environment in influencing diet quality (Clary et al., 2015, 2016; Mason et al., 2013). Moreover, an expanding body of research indicates the presence of spatial disparities in food access, with individuals residing in more socioeconomically deprived and rural areas being less likely to have access to healthy food environments (Larson et al., 2009; Black et al., 2014; Losada-Rojas et al., 2021; Vilar-Compte et al., 2021; Mackenbach et al., 2019). Nonetheless, the existing evidence linking neighborhood food environments to diet quality remains inconclusive, primarily due to methodological challenges inherent to relevant research (Charreire et al., 2010; Turner et al., 2021; Bivoltzis et al., 2018; Caspi et al., 2012; Kirkpatrick et al., 2014; Lytle and Sokol, 2017). In particular, heterogeneity in the classification of food outlets as healthy or less healthy, the selection of spatial exposure measurements (density vs proximity, absolute vs. relative measures), and the geographic delimitation of the exposure areas of interest (census tract vs. buffer zone, Euclidian vs. network distance, size of the buffers, etc.) make the collation and interpretation of research findings difficult (Charreire et al., 2010; Cobb et al., 2015; Wilkins et al., 2017). As people are exposed to different residential environments over the course of their lives, the temporal aspect of environmental exposure is also crucial to better capture how neighborhoods shape health outcomes. The use of longitudinal data is therefore particularly important for examining the effect of average and changing exposure to various food outlets on eating behaviors. Yet, so far, there is a lack of longitudinal studies, limiting the ability to draw causal associations between food environments and diet (Turner et al., 2021; Bivoltzis et al., 2018; Caspi et al., 2012; Kirkpatrick et al., 2014; Lytle and Sokol, 2017). Longitudinal observational studies, in particular, provide opportunities to delve into individuals' lived experiences of the food environment and diet in real-life settings, thereby offering insights that strengthen the basis for causal inference. Some observational studies provided longitudinal evidence of an association between local food environments and diet quality (Richardson et al., 2015; Rummo et al., 2015, 2017; Gao et al., 2022; Boone-Heinonen et al., 2011b; Bivoltzis et al., 2020) and health outcomes such as obesity (Acciai et al., 2022; Gibson, 2011; Green et al., 2021; Boone-Heinonen et al., 2013; Hobbs et al., 2023), with stronger associations observed for vulnerable socially disadvantaged groups (Gao et al., 2022; Rummo et al., 2015; Boone-Heinonen et al., 2011b; Acciai et al., 2022; Green et al., 2021).

However, null results have mostly been reported in causal impact studies using randomized controlled trials or quasi-experimental designs (Atanasova et al., 2022), contributing to the overall inconclusiveness of the evidence. Furthermore, existing studies have been mostly conducted in urban settings within the United States, and evidence from other countries is notably lacking. In particular, neighborhood disparities regarding access to healthy food environments in European settings need to be further explored to understand whether they can exacerbate food-related health inequalities in both urban and rural contexts (Larson et al., 2009; Black et al., 2014; Vilar-Compte et al., 2021; Mackenbach et al., 2019).

In view of these limitations, the main objective of our study was to study the effect on diet quality of 9-year average and change in exposure to residential food environments. In the absence of consistent results concerning the choice of the most appropriate spatial exposure (Clary et al., 2016; Thornton et al., 2020; Pinho et al., 2019), we assessed exposure to food retailers using both absolute and relative measurements. Our main hypotheses were as follows: 1) greater average and increased exposure to a healthy food environment is associated with better diet quality, 2) associations are stronger for urban residents, 3) relative exposure measurements of the food environments will better explain variability in diet quality over time, compared to absolute exposure measurements. We also tested whether the associations varied by neighborhood socioeconomic status.

2. Materials and methods

2.1. Study population and design

We used data of respondents who took part in the two waves of the ORISCAV-LUX study, a nationwide population-based survey monitoring cardiometabolic health within the adult population of the Grand Duchy of Luxembourg. The small size of the country, together with its rapid population growth, offers a unique opportunity to study the time-varying effects of local food environments at a national scale, as well as within different degrees of urbanicity. The first survey wave (ORISCAV-LUX 1) was conducted from 2007 to 2009 and included a nationally representative sample of 1432 participants aged 18–69. Participants were selected from the National Health Insurance Registry, using a stratified random sampling method based on age, sex, and district (Alkerwi et al., 2010). A follow-up (ORISCAV-LUX 2) was conducted from 2016 to 2017. Some 46% (n = 660) of respondents from the initial survey agreed to participate in the follow-up, and additional recruitment was performed to deal with the drop in the number of participants (Alkerwi et al., 2019). In both waves, participants filled in a series of questionnaires on demographic and socioeconomic characteristics, personal and family disease history, lifestyles, and health. All questionnaires were available in French, English, German, and Portuguese. Details about the study design have been previously published (Alkerwi et al., 2010, 2019). For the present study, we only included participants who participated in both waves (n = 660). We further excluded those who did not want their data to be reused (n = 27), those with no dietary data (n = 59), and those with implausible energy intake levels: <500 kcal/d or >6000 kcal/d (n = 8). These exclusions led to a final sample of 566 respondents. Participants in the final sample had similar socio-demographic characteristics to the ORISCAV-LUX 1 study population, with the exception of a smaller percentage of people with lower education (Additional file 1). The study was approved by the Luxembourg National Ethics Committee for Research (Ref: 202,104/03 V2.0).

2.2. Dietary assessment and diet quality

During both survey waves, the participants' typical dietary intake over the previous three months was assessed using a semi-quantitative food frequency questionnaire (FFQ) (Sauvageot et al., 2013a). In ORISCAV-LUX 1, the FFQ consisted of 134 items categorized into nine

food groups: starchy foods, fruits, vegetables, meat-poultry-fish-eggs, prepared dishes, dairy products, fats, drinks (alcoholic and non-alcoholic), and miscellaneous. The FFQ's detailed descriptions and its validation against three-day dietary records and nutritional biomarkers have been reported elsewhere (Sauvageot et al., 2013a, 2013b). In ORISCAV-LUX 2, some questions were divided into several sub-questions, resulting in a revised 174-item FFQ. For each food item, participants were asked to report the frequency of consumption and portion size. The frequency of consumption was evaluated on a six-item scale (rarely or never, one to three times a month, one to two times a week, three to five times a week, once a day, two or more times a day). Energy and nutrient contents of all foods was estimated using the French ANSES-Ciqual food composition database (French Agency for Food and Environmental and Occupational Health & Safety). The daily food and nutrient intakes were calculated by multiplying the frequency of consumption by the portion sizes of all food items.

The participants' overall diet quality was assessed using The Diet Quality Index-International (DQI-I) (Kim et al., 2003), which has been established as a reliable predictor of various serum and metabolic biomarkers of chronic disease risks in the ORISCAV-LUX study (Vahid et al., 2023). The DQI-I was calculated at both waves according to the method of Kim et al. (2003). This index includes 17 items accounting for four major aspects of a healthy nutritious diet: variety, adequacy, moderation, and overall balance (Kim et al., 2003). The variety section assesses whether the diet contains a wide range of foods from the five major food groups (protein sources, dairy/beans, grains, fruits, and vegetables), as well as variety within protein sources. The adequacy section evaluates whether the diet provides an adequate intake of essential food groups (fruits, vegetables, and grains) and nutrients (fiber, protein, iron, calcium, and vitamin C). The moderation section assesses the consumption of empty-calorie food and nutrients (total fat, saturated fat, cholesterol, and sodium), that are related to chronic diseases and that should be restricted. The overall balance section assesses the balance between energy intake from macronutrients and fatty acids. The DQI-I score ranges from 0 to 100, with a higher score indicating a higher-quality diet.

2.3. Exposure to local retail food environments

Data collection and reporting were carried out in accordance with the Geo-FERN reporting framework (Additional file 2) (Wilkins et al., 2017). The list of food outlets at the national level was retrieved at both waves using the Luxembourg Business Directory data from National Institute of Statistics and Economic Studies of Luxembourg (Répertoire des entreprises luxembourgeoises, STATEC) from 2009 to 2017, and further categorized into 8 types - supermarkets, small grocers, convenience stores (which are located at gas stations in Luxembourg), bakeries, butchers, fish mongers, fast-food outlets, and sit-down restaurants. Details on methods and sources used to extract the food outlets are available in Additional file 3.

Table 1

Description and classification of measurements of local retail food environment exposure used in the study.^a

Exposure measurements	Description
Simple absolute measurements	
Density of healthy food outlets	# healthy food outlets/road network buffer area (km ²)
Density of less healthy food outlets	# less healthy food outlets/road network buffer area (km ²)
Complex absolute measurements	
Spatial access to healthy food outlets	$\sum(1/\text{road network distance to healthy food outlets in the road network buffer})$
Spatial access to less healthy food outlets	$\sum(1/\text{road network distance to less healthy food outlets in the road network buffer})$
Complex relative measurements	
Proportion of healthy food outlets	# of healthy food outlets/# of total food outlets in the road network buffer
Proportion of less healthy food outlets	# of less healthy food outlets/# of total food outlets in the road network buffer

^a Healthy food outlets include supermarkets, greengrocers, open markets, and fishmongers. Less healthy food outlets include fast-food outlets, convenience stores, small grocers, butchers and bakeries.

In light of the lack of a universally accepted definition to classifying food outlets based on their level of healthiness, we used the widely-accepted definition from the US Center for Disease Control and Prevention (Centers for Disease Control and Prevention, 2011). Hence, we classified supermarkets, greengrocers, and open markets that are the major sources of fruits and vegetables in the retail food environment as "healthy" food outlets, and fast-food outlets, convenience stores, and small groceries as "less healthy" food outlets. Based on the current understanding of what constitutes a healthy diet (Cena and Calder, 2020), we further classified bakeries and butchers as less healthy, because they mainly offer foods that should be limited, such as fatty and processed meats, foods rich in saturated fats, refined grains, and salty and sugary products, whereas fishmongers were classified as healthy. Sit-down restaurants were not considered in the study, as they provide a large variety of both healthy and less healthy meals, and their association with diet quality remains poorly understood (Wellard-Cole et al., 2022). Each participant's home address and the addresses of the food outlets were geolocated using ArcGIS (Version 9.3.1; ESRI, Redlands, CA, USA, 2010).

We investigated both availability and accessibility dimensions of spatial exposure to food outlets within the neighborhood of residence (referred to here as the "local retail food environment") with six different measurements (Table 1). Exposure measurements were calculated for each individual and for each wave in order to account for relocation and change in local retail food environment. First, simple absolute measurements were computed as the density per square kilometer of healthy and of less healthy food outlets. We then computed the spatial access to healthy and to less healthy food outlets by summing up the inverse of the road network distance between each participant's home address and the food outlets within a specified buffer (Pinho et al., 2019). The spatial access variable has the advantage of providing information on both proximity and availability, with higher values indicating that participants live within a short distance of a large number of food outlets (Pinho et al., 2019). Lastly, we computed the relative numbers of healthy and less healthy food outlets as proportions (% of healthy and % of less healthy food outlets) (Clary et al., 2015). Incomputable ratios (for participants with no food outlets in their neighborhood) were replaced by zero values (Thornton et al., 2020). These six measurements were calculated around each participant's home address within a 1000 m road network buffer (equivalent to a 10–15 min walk), which is a commonly-used metric for defining residential neighborhood food environments (Wilkins et al., 2019). The road network was obtained from the BD-L-TC topographic database (version 2015) provided by the Administration of Cadaster and Topography.

2.4. Covariates

The individual-level covariates were collected as a part of the ORISCAV-LUX study. The time-invariant covariates used in the present study were sex and country of birth (Luxembourg, other European

country, or non-European country), and the time-varying covariates were age, resource perception (difficult, easy, or refuse to answer), working status (employed, not employed, stay-at-home parent, disabled, or retired), educational level (no diploma, secondary education, or higher diploma), marital status (married/living with partner, single/never married, or divorced/widowed), and presence of a child in the household (yes or no).

Based on previous research (Carpentier et al., 2006), the degree of urbanicity was established on the basis of a six-level typology of communes considering varying degrees of urbanicity and morpho-functional contexts in Luxembourg, and further grouped into two main categories: urban areas (dense cities, first ring, second ring, and former mining area) and rural areas (distant suburbs and rural communes). Neighborhood-level socioeconomic status (SES) is also an important confounding factor in observational studies on food environments and health (Mohammed et al., 2019). Principal Component Analysis (PCA) was used to identify patterns of neighborhood deprivation (Messer et al., 2006; Lian et al., 2011; Su et al., 2017; Pampalon et al., 2009), based on six indicators: employment (% of residents with a permanent, fixed-term, or temporary contract), occupation (% of blue-collar workers), income (monthly gross total wage), social assistance benefits (% domestic community receiving the guaranteed minimum income supplementary allowance, and percentage of the domestic community receiving cost-of-living allowance), and housing prices (average sales prices in euros per m²) (see Additional file 4). Two factors were retained considering eigenvalues >1 and a break point in the Scree test (Cattell, 1966; Kaiser, 1960): one factor representing material deprivation, with high loadings on employment, occupation, income, and housing prices; and one factor representing social deprivation, with high loadings for social assistance benefits. These two factors explained 71.3% of the total variance. Details on factor patterns, eigenvalues, and factor loadings are provided in Additional file 5.

2.5. Statistical analysis

The DQI-I index scores at baseline and at follow-up were compared via a Wilcoxon Signed-Rank test after observing some deviations from normality of the differences. Age (continuous) and DQI-I values were compared between urban and rural subgroups at baseline using a two-sample *t*-test, following assessment of normality and homogeneity assumptions. The categorical variables were also compared at baseline between rural and urban subgroups via a series of Fisher's exact tests. Missing values were dealt with through Multiple Imputation by Chained Equations (MICE) using the *mice* R package. The number of copies of imputed datasets was set to the percentage of incomplete cases (Von Hippel, 2009). All the variables used in the subsequent analyses were included in the imputation model (Moons et al., 2006). Item-level imputations were performed, with calculations of indices such as the DQI-I score after imputations. The method of imputation used was Fully Conditional Specification (FCS) (van Buuren, 2007). Fifteen imputed datasets were created. Further modelling was performed on the imputed datasets.

We investigated both cross-sectional (at baseline) and longitudinal associations between local retail food environments and diet quality using linear mixed models, as these models are particularly suitable for clustered repeated measurements (Subramanian, 2004). Longitudinal exposure to the local retail food environment was characterized by two different constructs: average exposure (defined as the average exposure between the two waves), and change in exposure (defined as the difference in exposure between the two waves). Average exposure variables were categorized as low, intermediate, and high exposure, based on sample tertiles. Change in exposure was categorized as no change ($\Delta = 0$), decrease ($\Delta < 0$), or increase ($\Delta > 0$). Models for average exposure investigated the average effect on DQI-I of exposure to local retail food environments across the two waves. Models for change further included an interaction term between the change in exposure to retail food

environments and time, to test the effect of changes in exposure to local retail food environments on change in DQI-I between the two waves. Separate models were fitted for baseline, average exposure, and change in exposure. All models included a random intercept for participants nested within the six-level typology of communes (Carpentier et al., 2006), and were adjusted for individual-level covariates and the two scores of neighborhood SES (material and social deprivation factors) derived from PCA. Estimates (β) and 95% confidence intervals (CI) from the 15 imputed datasets were summarized using PROC MIANALYZE (SAS Institute, Inc., Cary, North Carolina), for the total population and separately for urban and rural residents. Potential effect modification by neighborhood SES was investigated by adding a multiplicative interaction term between two scores of neighborhood SES and food environment exposure measurements (for the model on average effect), or by testing a triple interaction with food environment exposure and time (for the model on exposure change). Only significant interaction terms according to a type III test (F-test *p*-value <0.05) were retained for further in-depth analysis.

2.6. Sensitivity analyses

To assess the robustness of our findings, we conducted different sensitivity analyses. First, we excluded participants with no food outlets in their neighborhood, to ensure that the results were not driven by the added zero values (Thornton et al., 2020). Second, we compared the analysis on imputed data with the analysis on non-imputed data. Third, for the change in exposure to local food environments, we tested sensitivity to the categorization using tertiles instead of $\Delta = 0$ as thresholds to create the categories. Fourth, we tested the sensitivity of a more-restrictive definition of healthy and less healthy food outlets that excluded specialty food stores (bakeries, butchers, and fishmongers). We also tried only including fast-food outlets and convenience stores in the definition of less healthy food outlets, as they probably constituted the most unhealthy food outlets in Luxembourg. Lastly, we ran a model using a 2000 m road network buffer size, as rural residents are likely to rely on motorized transport modes and travel more than 1000 m to access food outlets.

All the statistical analyses were performed using R version 4.2.3 (R Foundation for Statistical Computing, Vienna, Austria) and SAS version 9.4 (SAS Institute, Cary, NC, USA), and a two-tailed *p*-value <0.05 was considered statistically significant.

3. Results

3.1. Descriptive statistics

Of the 566 participants considered for this study, the mean baseline age was 44.4 years, 50.2% were women, and 69.3% lived in urban areas. At baseline, urban residents were more likely to be better educated, and less likely to live with a partner and to be born in Luxembourg, compared with rural residents (Table 2). There was a significant decrease of DQI-I between the two waves from 62.4 to 61.0, mainly driven by a worsening in the moderation sub score (Table 3).

Fig. 1 shows the location of healthy and less healthy food outlets in the Grand Duchy of Luxembourg for both waves of the study. Retail food environment at baseline was dominated by less healthy food outlets compared with healthy ones ($n = 629$ vs. $n = 147$). The number of less healthy food outlets increased by 56.3% over the 9-year period, mainly due to a seven-fold increase in fast-food outlets and a two-fold increase in bakeries, while the number of healthy food outlets stayed relatively stable over time (+26.5% over time). Spearman correlation coefficients for the six exposure measurements were similar for both waves, ranging from -0.29 (between the proportion of healthy and less healthy food outlets at wave 2) to 0.95 (between the density and proportion of healthy food outlets at wave 1) (Additional file 6). The mean (SD), median (IQR), and tertiles of the longitudinal measurements (average

Table 2
Selected baseline characteristics of the study population, n = 566 adults in the ORISCAV-LUX study (2007–2017).

	Urban residents (n = 392)	Rural residents (n = 174)	P-value ^a
Mean (SD) DQI-I, total	62.7 (5.9)	61.9 (6.1)	0.141
Mean (SD) age, years	44.8 (12.1)	43.5 (12.9)	0.243
Women, n (%)	197 (50.3)	87 (50.0)	0.955
Resource perception, n (%)			0.331
Difficult	57 (14.5)	26 (14.9)	
Easy	315 (80.4)	144 (82.8)	
Refuse to answer	20 (5.1)	4 (2.3)	
Working status, n (%)			0.757
Employed	277 (70.7)	116 (66.7)	
Not employed	33 (8.4)	17 (9.8)	
Stay-at-home parent	38 (9.7)	21 (12.1)	
Disabled or retired	44 (11.2)	20 (11.5)	
Education level, n (%)			0.002
No diploma	64 (16.3)	28 (16.1)	
High school or vocational diploma	173 (44.1)	103 (59.2)	
Higher diploma	153 (39.0)	43 (24.7)	
NA	2 (0.5)	0 (0)	
Marital status, n (%)			0.014
Married/living with partner	285 (72.7)	142 (81.6)	
Single/never married	60 (15.3)	25 (14.4)	
Divorced/widowed	47 (12.0)	7 (4.0)	
Country of birth, n (%)			0.002
Luxembourg	226 (57.7)	127 (73.0)	
Other European country	140 (35.7)	41 (23.6)	
Non-European country	26 (6.6)	6 (3.4)	
Presence of a child in the household, n (%)			0.275
Yes	202 (51.5)	81 (46.6)	
No	190 (48.5)	93 (53.4)	
Relocation, n (%)			0.005
Yes	134 (34.2)	39 (22.4)	
No	258 (65.8)	135 (77.6)	

^aP-value for a two-sample *t*-test of equality of means (continuous variables) or Fisher's exact test of significance of association (categorical variables).

Table 3
Diet Quality Index-International (DQI-I) scores and components.

Component	Score ranges ^a	Wave 1	Wave 2	P-value ^b
	points	mean (SD)	mean (SD)	
DQI-I, total	0–100	62.4 (6.0)	61.0 (6.0)	<0.001
Variety	0–20	20 (0.3)	19.9 (0.6)	–
Overall food group variety	0–15	15 (0.3)	15 (0.4)	–
Within-group variety for protein sources	0–5	5.0 (0.1)	5.0 (0.3)	–
Adequacy	0–40	29.8 (4.5)	30.1 (4.3)	–
Vegetable group	0–5	2.8 (1.3)	2.9 (1.2)	–
Fruit group	0–5	3.5 (1.5)	3.5 (1.5)	–
Grain group	0–5	1.6 (0.7)	1.5 (0.6)	–
Fiber	0–5	4.0 (0.9)	3.9 (0.9)	–
Protein	0–5	5.0 (0.1)	5.0 (0.2)	–
Iron	0–5	4.4 (1.0)	4.6 (0.9)	–
Calcium	0–5	4.3 (1.0)	4.0 (1.2)	–
Vitamin C	0–5	4.4 (1.1)	4.5 (1.0)	–
Moderation	0–30	12.4 (4.8)	11.0 (4.5)	–
Total fat	0–6	0.4 (1.2)	0.1 (0.6)	–
Saturated fat	0–6	5.9 (0.4)	5.9 (0.6)	–
Cholesterol	0–6	3.6 (2.5)	2.9 (2.5)	–
Sodium	0–6	2.4 (2.4)	2.2 (2.4)	–
Empty calorie foods	0–6	0 (0.3)	0 (0.2)	–
Overall balance	0–10	0.3 (0.9)	0.3 (0.8)	–
Macronutrient ratio ^c	0–6	0.1 (0.6)	0.2 (0.8)	–
Fatty acid ratio ^d	0–4	0.2 (0.7)	0 (0.2)	–

^a See Kim et al. (2003) for details regarding scoring criteria.

^b P-value for difference between Wave 1 and Wave 2 using Wilcoxon Signed-Rank test after observing some deviations from normality of the differences.

^c Ratio of carbohydrate: protein: fat.

^d Ratio of polyunsaturated fatty acids (PUFA): monounsaturated fatty acids (MUFA): saturated fatty acids (SFA).

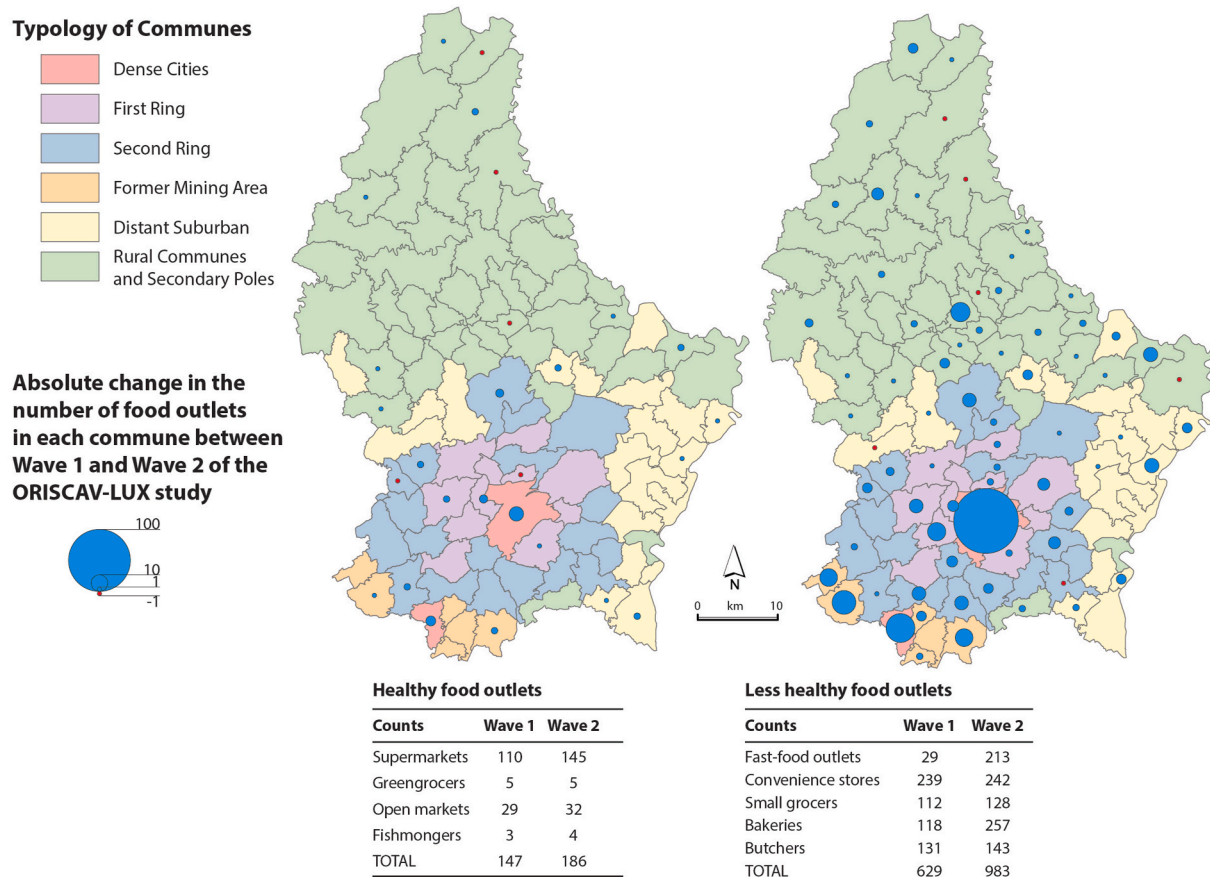


Fig. 1. Change in the number of healthy and less healthy food outlets between Wave 1 (2007) and Wave 2 (2017) of the ORISCAV-LUX study, in the Grand Duchy of Luxembourg.

The typology of communes was derived from previous work conducted in 2006 (Bivoltsis et al., 2020), based on varying degrees of urbanicity and morpho-functional contexts in Luxembourg. Dense cities, the first ring, second ring, and former mining areas were considered as urban areas. Distant suburbs, rural communes, and secondary poles were considered rural areas.

and change) of the food environment are presented in Additional file 7. Of the 566 participants, 107 had no exposure to food outlets within 1000 m of their home address at both waves (11% of urban residents and 37% of rural residents) (data not shown).

3.2. Local retail food environments and diet quality

There was no cross-sectional association between any of the retail food environment exposure measurements and DQI-I at baseline (Additional file 8). Associations between DQI-I and average exposure and change in exposure to local retail food environments are shown in Table 4. Exposure to healthy food outlets was not significantly associated with DQI-I. Participants with high (vs. low) long-term average spatial access to less healthy food outlets had significantly lower DQI-I ($\beta = -1.25$, 95% CI: $-2.29, -0.22$). Average exposure to intermediate and high proportions of less healthy food outlets was also associated with lower DQI-I; that is, -1.35 (95% CI: $-2.32, -0.38$) and -1.24 (95% CI: $-2.15, -0.33$), respectively. There were no significant associations between change in exposure to less healthy food outlets and DQI-I.

Analyses conducted separately for urban and rural residents are presented in Fig. 2. Long-term average exposure to less healthy food outlets in terms of spatial access ($\beta_{intermediate} = -1.53$, 95% CI: $-2.73, -0.33$; $\beta_{high} = -2.01$, 95% CI: $-3.38, -0.63$) and proportion ($\beta_{intermediate} = -1.96$, 95% CI: $-3.20, -0.73$; $\beta_{high} = -1.96$, 95% CI: $-3.04, -0.73$) was only significantly associated with lower DQI-I among

urban residents. A trend was also observed for the density of less healthy food outlets, albeit non-significant. Among rural residents, an increase in the density of and spatial access to healthy food outlets was associated with a decrease in DQI-I over time; that is, -3.01 (95% CI: $-5.55, -0.48$) and -3.80 (95% CI: $-5.63, -0.97$), respectively. Moderation analyses showed no significant interactions between the food environment exposure measurements and the two scores of neighborhood SES (material and social deprivation factors) in the total population and separately for urban and rural residents (data not shown).

3.3. Sensitivity analyses

The results of the main analyses were consistent with the results of alternative models excluding participants with no food outlets in their neighborhood (Additional file 9) or when running the analyses on the non-imputed dataset (Additional file 10). Associations between changes in exposure to local retail food environments and DQI-I also were similar when using tertiles to create the categories of change in exposure (Additional file 11). Associations were no longer significant using the restricted definition of healthy and less healthy food outlets (Additional file 12). Limiting the definition of less healthy food outlets to fast-food outlets and convenience stores slightly attenuated the associations between the spatial access to and proportion of less healthy food outlets and DQI-I, but further revealed a significant negative association between average exposure to a high density of less healthy food outlets and DQI-I among urban residents (Additional file 13). Associations between

Table 4Estimates (β) and 95% confidence intervals (CI) for associations of average exposure and change in exposure to the local retail food environment with DQI-I.^a

	Density		Spatial access		Proportion	
	β (95% CI)	P-value	β (95% CI)	P-value	β (95% CI)	P-value
Healthy food outlets^b						
Average exposure^c						
Low	ref.	–	ref.	–	ref.	–
Intermediate	0.09 (–0.93, 1.12)	0.856	–0.01 (–1.13, 1.1)	0.980	–0.13 (–1.20, 0.93)	0.806
High	–0.51 (–1.45, 0.43)	0.286	–0.33 (–1.25, 0.6)	0.493	–0.31 (–1.21, 0.58)	0.490
Change in exposure^d						
Decrease	0.36 (–1.15, 1.87)	0.644	0.43 (–0.96, 1.81)	0.546	0.09 (–1.04, 1.21)	0.878
No change	ref.	–	ref.	–	ref.	–
Increase	–0.08 (–1.22, 1.06)	0.891	–0.22 (–1.40, 0.96)	0.718	–0.05 (–1.27, 1.18)	0.941
Wave x decrease	–0.14 (–1.86, 1.59)	0.878	–0.01 (–1.55, 1.53)	0.993	0.13 (–1.06, 1.31)	0.834
Wave x no change	ref.	–	ref.	–	ref.	–
Wave x increase	–0.1 (–1.35, 1.15)	0.877	–0.38 (–1.7, 0.93)	0.566	–0.31 (–1.68, 1.07)	0.662
Less healthy food outlets^b						
Average exposure^c						
Low	ref.	–	ref.	–	ref.	–
Intermediate	–0.57 (–1.5, 0.36)	0.230	–0.82 (–1.75, 0.11)	0.084	–1.35 (–2.32, –0.38)	0.006
High	–0.85 (–1.9, 0.20)	0.113	–1.25 (–2.29, –0.22)	0.018	–1.24 (–2.15, –0.33)	0.008
Change in exposure^d						
Decrease	0.33 (–1.18, 1.84)	0.667	0.09 (–1.35, 1.52)	0.905	0.8 (–0.24, 1.84)	0.134
No change	ref.	–	ref.	–	ref.	–
Increase	0.12 (–0.94, 1.18)	0.826	–0.24 (–1.30, 0.83)	0.666	0.04 (–1.21, 1.29)	0.949
Wave x decrease	–0.71 (–2.44, 1.01)	0.419	–0.88 (–2.47, 0.71)	0.276	0.08 (–1.33, 1.49)	0.913
Wave x no change	ref.	–	ref.	–	ref.	–
Wave x increase	0.34 (–0.79, 1.47)	0.558	0.71 (–0.42, 1.83)	0.219	0.09 (–1.04, 1.22)	0.874

DQI-I: Diet Quality Index-International.

Significant results are highlighted in bold.

^a All models were adjusted for sex, age, resource perception (difficult, easy, or refuse to answer), working status (employed, not employed, stay-at-home parent, disabled, or retired), educational level (no diploma, secondary education, or higher diploma), marital status (married/living with partner, single/never married, or divorced/widowed), country of birth (Luxembourg, other European country, or non-European country), and presence of a child in the household (yes or no), as well as two scores of neighborhood SES (social and material factors) derived from PCA.

^b Healthy food outlets include food outlets that provide fresh fruit and vegetables: supermarkets, greengrocers, open markets, and fishmongers. Less healthy food outlets include those that mainly provide highly-processed foods: fast-food outlets, convenience stores, small grocers, butchers, and bakeries.

^c Average exposure between the two waves. Values were categorized as low, intermediate, and high exposure based on tertiles.

^d Difference (Δ) in exposure between the two waves. Values were categorized as follows: no change ($\Delta = 0$), decrease ($\Delta < 0$), increase ($\Delta > 0$).

the average spatial access to and proportion of less healthy food outlets and DQI-I were no longer significant when using a 2000 m road network buffer (Additional file 14).

4. Discussion

This study aimed to provide a more comprehensive understanding of the effect of local retail food environments on the population's diet quality over a 9-year period. Overall, our findings contribute to the growing body of evidence concerning the relevance of local food environments shaping dietary behaviors. We further observed strong heterogeneity in findings, depending on the spatial measurements of the local food environment, temporal exposure, and urbanicity. Using both absolute and relative measurements of varying complexity, we found that a high long-term average exposure (but not change) to less healthy food outlets — whether in terms of spatial access or proportion — was associated with a 1.25 lower DQI-I on average (hypothesis 1). Although we recognize that the effect of these associations is small, they could affect long-term health. For instance, a pooled analysis of 10 European countries has shown that a 1-SD increase in DQI-I was linked to a reduced risk of all-cause, cardiovascular diseases, and cancer mortality after 10 years (Lassale et al., 2016). Past studies have underscored the adverse impacts of cumulative exposure to deprived neighborhoods on cardiovascular health, functional health, and mortality at later ages (Clarke et al., 2013; Jimenez et al., 2019). These findings align with the theory of cumulative disadvantage, indicating that exposure to economic, social, and environmental challenges accumulates over time, shaping health inequalities throughout the life course (Ferraro and Kelley-Moore, 2003). Our research offers fresh insights into how long-term exposure to specific food environments during adulthood can

influence diet — a topic underexplored in prior studies. Despite a significant increase in less healthy food outlets at the national scale, the change within the immediate neighborhoods surrounding our participants was limited. To our knowledge, only one previous study has compared average exposure to and change in food environments in relation to diet quality; the study also found a significant association with average exposure, but not with change over 10 years, likely due to limited changes over time (Gao et al., 2022). Yet, other longitudinal observational studies found that being exposed to a deteriorating food environment over time was associated with increased fast-food consumption (Richardson et al., 2015; Boone-Heinonen et al., 2011b), unhealthy food intake (Bivoltsis et al., 2020), BMI and obesity-related outcomes (Acciai et al., 2022; Gibson, 2011; Green et al., 2021; Hobbs et al., 2023). More longitudinal studies over extended follow-up periods and in different settings are therefore needed to further investigate this little explored area.

We found stronger links between food environments and diet quality in urban areas, supporting hypothesis 2. This aligns with broader evidence suggesting divergent responses to food environments between urban and rural residents (Larson et al., 2009; Vilar-Compte et al., 2021). Similar results were observed in a Dutch study, where proximity to fast-food outlets was associated with fast-food intake in urban and peri-urban areas, but not in rural areas (Bernsdorf et al., 2017). It is acknowledged that rural residents face greater issues related to food access, because of reduced proximity and public transport resources, although evidence from non-US settings is scarce (Larson et al., 2009; Losada-Rojas et al., 2021; Vilar-Compte et al., 2021). Given the limited number of food outlets in rural areas in Luxembourg and knowing that the country has the highest per capita car ownership in the EU (European Commission), it is likely that rural residents purchase food from

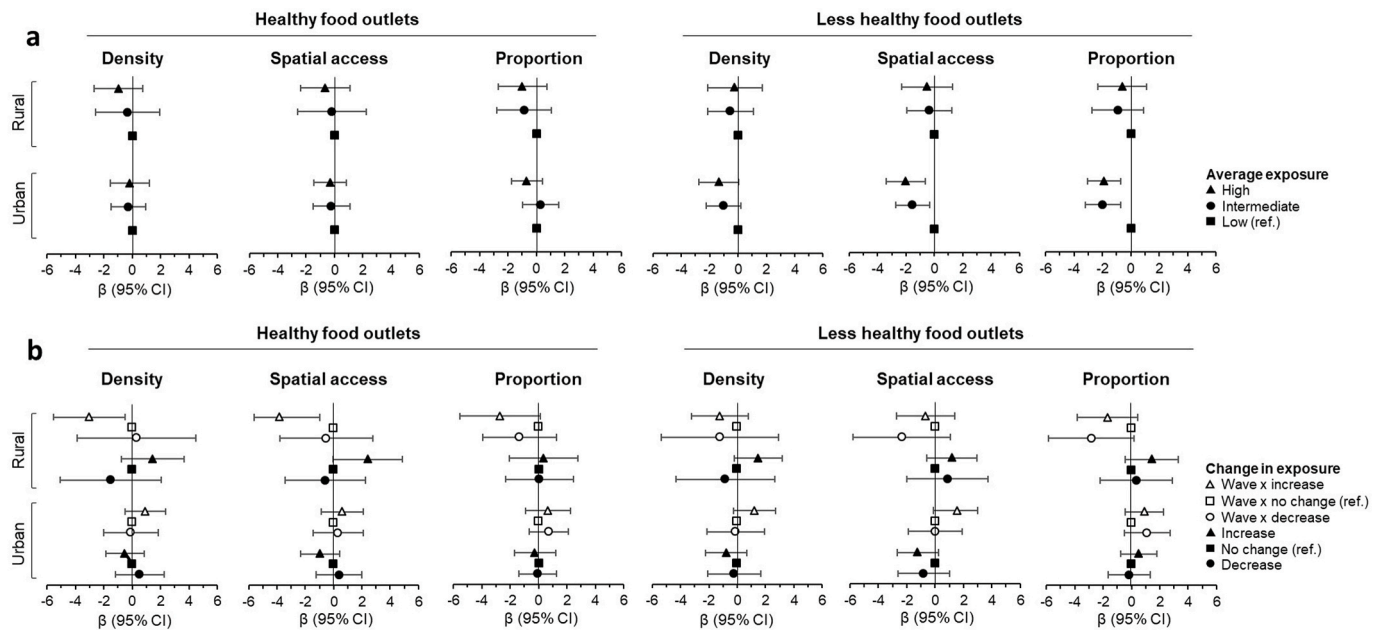


Fig. 2. Estimates (β) and 95% confidence Intervals (CI) for associations of average exposure (a) and change in exposure (b) to local retail food environment with DQI-I, among urban and rural residents.

DQI-I: Diet Quality Index-International. Healthy food outlets include supermarkets, greengrocers, open markets, and fishmongers. Less healthy food outlets include fast-food outlets, convenience stores, small grocers, butchers, and bakeries. All models were adjusted for sex, age, resource perception (difficult, easy, or refuse to answer), working status (employed, not employed, stay-at-home parent, disabled, or retired), educational level (no diploma, secondary education, or higher diploma), marital status (married/living with partner, single/never married, or divorced/widowed), country of birth (Luxembourg, other European country, or non-European country), and presence of a child in the household (yes or no), as well as two scores of neighborhood SES (social and material factors) derived by PCA. Average exposure was calculated by the average exposure between the two waves. Values were categorized as low, intermediate, and high. Change in exposure was calculated as the difference (Δ) in exposure between the two waves. Values were categorized as follows: no change ($\Delta = 0$), decrease ($\Delta < 0$), increase ($\Delta > 0$).

outside of their neighborhood, near their workplace, school, or other destinations. In neighborhood and health research, a common limitation is focusing solely on residential spaces, neglecting non-residential environments encountered through daily mobility (Perchoux et al., 2013). This bias in exposure measurement could explain the more limited associations between residential food environments and diet quality in rural areas, advocating for spatio-temporal approaches that capture activity space to more accurately reflect individuals' daily exposure (Crawford et al., 2014).

We observed that two-thirds of the participants were exposed to a predominantly unhealthy food environment (>50% of the total number of food outlets). This result is particularly worrying, given that participants with intermediate average exposure to less healthy food outlets also exhibited poorer quality diets. Another important findings was the declining healthiness of the food environment over time, primarily due to a strong increase in fast-food outlets, predominantly in urban areas. Considering the established evidence linking exposure to fast-food outlets and poorer diet in urban areas (Athens et al., 2016; Bernsdorf et al., 2017; Boone-Heinonen et al., 2011a; Moore et al., 2009; Richardson et al., 2015; Dunn et al., 2012; Thornton et al., 2009; Rummo et al., 2017), one could reasonably assume that the increase in these outlets in Luxembourg has contributed to the observed association between average exposure to less healthy food environments and lower diet quality among urban residents. However, using more restricted definitions of “less healthy” food outlets attenuated this association, suggesting that other retailers (convenience stores, small grocers, bakeries, and butchers) also play a detrimental role in shaping purchasing and eating practices. While common indicators measuring the neighborhood food environments tend to omit specialty food stores (e.g., bakeries, butchers, fishmongers, and candy stores), our results support previous calls to broaden these indicators to encompass a greater number of food outlets, in order to obtain a more complete picture of the food landscape

and limit the risk of misleading results (Clary et al., 2015; Thornton et al., 2020; Ferdinands et al., 2023).

Consistent with previous research (Clary et al., 2015, 2016; Mason et al., 2013), relative measurements of food environments exhibited stronger and more consistent associations with diet quality than simple measurements such as density (hypothesis 3). Surprisingly, an increase in the density of healthy food outlets over time was associated with a decrease in DQI-I among rural residents. A major limitation of absolute measurements is that they do not give a complete picture of the food environment to which people are exposed, as food outlets, whether classified as healthy or not, are often spatially clustered (Clary et al., 2015). Given the limited increase in healthy food outlets over time, it is therefore likely that the concomitant stronger increase in less healthy food outlets could explain this unexpected results. Nevertheless, relative measurements are also not without limitations, and using proportions has also been criticized for not providing information on absolute quantities: for example, two neighborhoods with a different density of outlets but the same proportion of healthy and less healthy outlets are not equal (Thornton et al., 2020). In fact, it is somewhat simplistic to suggest that our findings also support the idea that relative measurements outperform absolute measurements (Clary et al., 2016; Thornton et al., 2020; Pinho et al., 2019). For example, we found long-term average spatial access to less healthy food outlets (i.e., an absolute measurement) to be associated with lower diet quality. This finding suggests that beyond availability measurements — either absolute or relative — other metrics, such as proximity, may also be important to consider when characterizing food environments. Although evidence suggests that availability measures may yield more significant and substantial effect sizes than accessibility measures, both offer distinct and complementary conceptualizations of spatial exposure (Bivoltzis et al., 2018). Since different measurements provide different information about environments (Clary et al., 2016; Thornton et al., 2020; Pinho

et al., 2019), we strongly encourage future studies to jointly investigate different spatial measurement methods, accounting for both availability and accessibility, in order to better capture the complexity of food environments, provide a better understanding of the implications of using these measurement methods, and consequently better guide effective contextual policy responses to unhealthy dietary behaviors.

Existing findings, albeit inconsistent, generally support the hypothesis that the associations between local food environments and diet quality are stronger for populations living in deprived neighborhoods (Larson et al., 2009; Black et al., 2014; Vilar-Compte et al., 2021; Mackenbach et al., 2019). The absence of a moderate effect of neighborhoods SES observed in our study aligns with previous findings indicating that socioeconomic segregation and disparities in food access are less pronounced in European settings than in US ones (Helbich et al., 2017; Macdonald et al., 2009). It is also possible that sample size limitations may have hampered the ability to detect significant interactions with neighborhood SES.

Our study has important strengths, including its longitudinal design, the nationwide scale of the cohort allowing for heterogeneity in individual and environmental characteristics, and the ability to adjust for various individual and neighborhood-level confounders. Despite these strengths, some limitations of the study should be mentioned. First, the ORISCAV-LUX study had only a single follow-up, and two time points lack temporal granularity to reflect true exposure to food environments over the time period, which limits causal inference (Ployhart et al., 2015; Wang et al., 2017). Second, self-reported dietary intake, even when compiled by trained personnel, is subject to social desirability bias and memory recall. Third, there is a risk that public directories may be incomplete, particularly for small retail food stores and in rural areas, as seen in US public directories (Wang et al., 2006; Longacre et al., 2011). Nevertheless, such errors are unlikely to vary systematically with diet quality. Fourth, although not measured in the study, changes in the in-store environment in terms of availability, affordability, prominence, and promotion may have encouraged less healthy shopping habits, subsequently leading to poorer quality of offered foods (Glanz et al., 2012). Similarly, this study did not account for other factors related to supply strategies, such as the use of online supply. Although further investigation of this question would provide an even more detailed understanding of the relationship between food landscaping and food behavior, it was out of scope of this study, especially as between 2007 and 2017, food delivery was still limited in Luxembourg. Fifth, the DQI-I may lack sensitivity to detect subtle dietary changes over time in response to food environments, potentially missing significant associations. Lastly, longitudinal approaches are not enough to guarantee unbiased causal inference, and the risk of self-selection bias regarding study participation and choice of residential neighborhood cannot be completely ruled out (Lu et al., 2022; Diez Roux, 2004). However, these approaches are a first step toward a better understanding of the relationship between food environments, diet, and health outcomes, and to guide the development of more rigorous experimental studies (Lovasi et al., 2012).

5. Conclusions

The study results showed how the food environment in Luxembourg deteriorated over 9 years, with a strong increase in the number of fast-food outlets in urban areas. We found longitudinal associations between greater exposure to less healthy food outlets and poorer diet quality. Associations were significant only when considering average exposure, complex measurements of local retail food environments (spatial access and proportion), and for urban residents only. Surprisingly, increased density and spatial access to healthy food outlets over time were associated with worsened DQI-I among rural residents. Given the substantial increase in the number of less healthy food outlets, the use of absolute measurements could potentially yield misleading results, as they might not comprehensively capture the overall healthiness of the

food environment. In light of our results, urban policy strategies targeting less healthy food outlets could play a key role in reducing unhealthy dietary behaviors and diet-related diseases in Luxembourg.

Ethics approval and consent to participate

The study was approved by the Luxembourg National Ethics Committee for Research (Ref: 202,104/03 V2.0). All participants to the ORISCAV-LUX 1 and 2 studies provided written consent. They were then informed about the MET'HOOD project and given the opportunity to object to the use of their data.

Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

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Conflicts of interest

None.

Ethical standards disclosure

This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving research study participants were approved by the Luxembourg National Ethics Committee for Research (Ref: 202,104/03 V2.0). All participants to the ORISCAV-LUX 1 and 2 studies provided written consent. They were then informed about the MET'HOOD project and given the opportunity to object to the use of their data.

Availability of data and materials

De-identified data may be available upon reasonable request if consent is provided by all authors and the ORISCAV study group. Requests to access the data should be directed to L.M. and C.P.

CRedit authorship contribution statement

Marion Tharrey: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Torsten Bohn:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Olivier Klein:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Dmitry Bulaev:** Writing – review & editing, Investigation, Formal analysis. **Juliette Van Beek:** Writing – review & editing. **Julie-Anne Nazare:** Writing – review & editing. **Manuel Franco:** Writing – review & editing. **Laurent Malisoux:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Camille Perchoux:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.healthplace.2024.103240>.

List of abbreviations:

BMI	Body mass index
CI	Confidence interval
DQI-I	Diet Quality Index-International
IQR	Interquartile range
NACE	Nomenclature of Economic Activities
ORISCAV-LUX	Observation of Cardiovascular Risk Factors in Luxembourg Study
PCA	Principal Component Analysis
SD	Standard deviation
SES	Socioeconomic status
WHO	World Health Organization

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