Impact of Land Use and Food Environment on Risk of Type 2 Diabetes: A National Study of Veterans, 2008–2018

Sandra India-Aldana[1], **Rania Kanchi**[1], **Samrachana Adhikari**[2], **Priscilla Lopez**[1], **Mark D. Schwartz**[3,4], **Brian D. Elbel**[5,6], **Pasquale E. Rummo**[1], **Melissa A. Meeker**[7], **Gina S. Lovasi**[7], **Karen R. Siegel**[8], **Yu Chen**[1,9], **Lorna E. Thorpe**[1,*]

[1]Division of Epidemiology, Department of Population Health, NYU Grossman School of Medicine, 180 Madison Avenue, 5th Fl., New York, NY, 10016, USA

[2]Division of Biostatistics, Department of Population Health, NYU Grossman School of Medicine, 180 Madison Avenue, 5th Fl., New York, NY, 10016, USA

[3]Division of Comparative Effectiveness and Decision Science, Department of Population Health, NYU Grossman School of Medicine, 180 Madison Avenue, 9th Fl., New York, NY, 10016, USA

[4]VA New York Harbor Healthcare System, 423 E 23rd, New York, NY, 10010, USA

[5]Division of Health and Behavior, Section on Health Choice, Policy and Evaluation, Department of Population Health, NYU Grossman School of Medicine, 180 Madison Avenue, 3rd Fl., New York, NY, 10016, USA

[6]NYU Wagner Graduate School of Public Service, 295 Lafayette Street, New York, NY, 10012, USA

[7]Drexel University Dornsife School of Public Health, 3215 Market St, Philadelphia, PA 19104, USA

[8]Division of Diabetes Translation, Centers for Disease Control and Prevention, Atlanta, GA, 30341, USA

[9]Department of Environmental Medicine, NYU Grossman School of Medicine, New York, NY, USA

Abstract

Background—Large-scale longitudinal studies evaluating influences of the built environment on risk for type 2 diabetes (T2D) are scarce, and findings have been inconsistent.

Objective—To evaluate whether land use environment (LUE), a proxy of neighborhood walkability, is associated with T2D risk across different US community types, and to assess whether the association is modified by food environment.

Methods—The Veteran's Administration Diabetes Risk (VADR) study is a retrospective cohort of diabetes-free US veteran patients enrolled in VA primary care facilities nationwide from January 1 2008, to December 31, 2016, and followed longitudinally through December 31, 2018. A total of 4,096,629 patients had baseline addresses available in electronic health records that

*Corresponding Author: Lorna E. Thorpe, Division of Epidemiology, Department of Population Health, New York University School of Medicine, 180 Madison Avenue, 5th Fl., New York, NY 10016, USA. Lorna.Thorpe@nyulangone.org.

were geocoded and assigned a census tract-level LUE score. LUE scores were divided into quartiles, where a higher score indicated higher neighborhood walkability levels. New diagnoses for T2D were identified using a published computable phenotype. Adjusted time-to-event analyses using piecewise exponential models were fit within four strata of community types (higher-density urban, lower-density urban, suburban/small town, and rural). We also evaluated effect modification by tract-level food environment measures within each stratum.

Results—In adjusted analyses, higher LUE had a protective effect on T2D risk in rural and suburban/small town communities (linear quartile trend test p-value <0.001). However, in lower density urban communities, higher LUE increased T2D risk (linear quartile trend test p-value <0.001) and no association was found in higher density urban communities (linear quartile trend test p-value=0.317). Particularly strong protective effects were observed for veterans living in suburban/small towns with more supermarkets and more walkable spaces (p-interaction=0.001).

Conclusion—Among veterans, LUE may influence T2D risk, particularly in rural and suburban communities. Food environment may modify the association between LUE and T2D.

1. Introduction

Diabetes prevalence has increased greatly in the past three decades, reaching 13.0% among US adults in 2018 (Centers for Disease Control and Prevention 2020b), a trend which parallels a similar rapidly growing obesity epidemic (Hales et al. 2020). Diabetes prevalence rates tend to cluster more starkly around rural areas and the southeast region of the country (Barker et al. 2011; Centers for Disease Control and Prevention 2020a, 2021; Dwyer-Lindgren et al. 2016; Loop et al. 2017; Lord et al. 2020). Trends and US geographic differences in risk of type 2 diabetes (T2D) may be driven by differential access to resources (Grintsova et al. 2014) and a disproportionate burden of environmental exposures (Jagai et al. 2020), differences in dietary behaviors (Davis et al. 2011; Liu et al. 2012; van Dam et al. 2002), which are influenced concomitantly by racial (Cheng et al. 2019; Egede et al. 2011; Lynch et al. 2015), socio-economic (SES) composition (Kanjilal et al. 2006), or socio-demographic changes (Commodore-Mensah et al. 2018; Hipp and Chalise 2015; Schneiderman et al. 2014). Substantial evidence indicates that built environment characteristics such as neighborhood walkability can have an impact on behaviors such as outdoor physical activity or walking (Borrell et al. 2004; Corriere et al. 2014; Creatore et al. 2016; Frank et al. 2004; Gaglioti et al. 2018; Krumm EM 2006; Murphy et al. 2007; Sharifi et al. 2016). Yet, research findings on the extent to which attributes of the built environment impact T2D risk, adjusting for other individual and neighborhood-level risk factors, are inconsistent. Most previous studies on neighborhood walkability and diabetes have either been cross-sectional or ecological in design (Creatore et al. 2016; Herrick et al. 2016; Jagai et al. 2020), had relatively short follow-up time periods (Sundquist et al. 2015), or included limited adjustment for potential confounding factors at the individual level (Herrick et al. 2016; Jagai et al. 2020). Some of the inconsistency of prior studies may also be due to limited geographic variation within a given study population as the built

environment may function differently in some community types compared to others. For example, while urban areas tend to be highly walkable and well-connected, rural areas are generally more car-dependent. In higher density urban areas, individuals may spend more time walking for errands and commuting, whereas in rural areas individuals may opt for a vehicle to travel what are often longer distances. Moreover, in the US there is a distinct spatial clustering of major risk factors for diabetes, such as hypertension (Samanic et al. 2020), obesity (Befort et al. 2012), and poor diet (Davis et al. 2011; Liu et al. 2012). Thus, opportunity for physical activity, and amenability for intervention, may differ across communities. To date, longitudinal evaluations of the association between neighborhood walkability and T2D risk are scarce (Auchincloss et al. 2009; Booth et al. 2019; Creatore et al. 2016; den Braver et al. 2018; Herrick et al. 2016; Jagai et al. 2020; Kartschmit et al. 2020; Sundquist et al. 2015) and has not been examined yet across community types.

In addition to neighborhood walkability, recent evidence shows that access to a healthy food environment may be linked to lower obesity levels (Briggs et al. 2019; Frank et al. 2009; Rundle et al. 2009; Singleton et al. 2016) and T2D (Mezuk et al. 2016). As suggested by prior studies linking neighborhood factors and cardiometabolic outcomes (Auchincloss et al. 2009; Fan et al. 2019; Herrick et al. 2016), the association between neighborhood walkability and T2D risk may be influenced by variation in adequate neighborhood resources promoting a healthy diet. However, no longitudinal research has yet formally evaluated the interaction between neighborhood walkability and food environment on T2D across rural and urban settings. We have empirical evidence that T2D incidence varies by community type (McAlexander et al. 2021), with higher incidence in urban settings for most of the country, and we hypothesize that the distribution of healthy food outlets may differentially affect the impact of neighborhood walkability on T2D across areas with distinct population densities. Therefore, we are interested in studying how walkability may play a role in T2D risk and how it interacts with the food environment across strata of community types.

The Diabetes LEAD (Location, Environmental Attributes, and Disparities) Network, a Centers for Disease Control and Prevention-funded collaboration between multiple academic institutions aiming to study the role of community-level factors and geographic differences on diabetes incidence (Hirsch et al. 2020), developed a census tract-level measure of land use environment (LUE) intended to describe the continuum of walkable to car-dependent neighborhoods. In this study, we use a large cohort of US veterans followed for approximately one decade to evaluate whether LUE, a proxy of a neighborhood's walkability, is associated with T2D risk, and whether its association is modified by food environment across different community types in the US. Prevalence and incidence of diabetes among VA patients is high (Avramovic et al. 2020; US Department of Veteran Affairs 2021), and the veteran population is large and spans nearly all regions and community types across the United States. We leveraged these attributes and the benefit of a single EHR system for all VA patients to evaluate modifiable built environment features that may help reduce T2D risk through tailored local legislation and resource allocation.

2. Methods

2.1 Study Population

The Veterans Administration Diabetes Risk (VADR) study is a large retrospective cohort of diabetes-free, US veteran primary care patients enrolled in VA facilities nationwide from January 1, 2008, to December 31, 2016, and followed longitudinally through December 31, 2018. The VADR cohort was developed using the VA EHR VINCI system, described elsewhere (Avramovic et al. 2020). The study uses electronic health records (EHRs) from the VA's Corporate Data Warehouse, a national repository of clinical and administrative data, available through the VA's Information Resource Center. The cohort had dynamic entry eligibility where participants enrolled at different time points. Eligibility criteria for the VADR cohort has been previously described (Avramovic et al. 2020; Davis et al. 2018). VA patients with at least two primary care visits at least 30 days apart within the last 5 years prior to study entry in any of the 168 VA Medical Centers and 1,053 VA Community Based Outpatient Clinics (Avramovic et al. 2020; Davis et al. 2018) were eligible for this study (n=6,082,246 excluding patients with no subsequent visits). Patients with potential evidence of prevalent diabetes as of January 1, 2008, or when enrolling in the dynamic cohort through December 31, 2016, were excluded. We used the same T2D diagnosis definition criteria mentioned in section 2.4 to exclude baseline cases. Loss to follow-up was recorded when an individual did not attend any VA appointments for more than 2 years. This study was supported by the Diabetes LEAD Network (Hirsch et al. 2020) and was approved by the Institutional Review Boards of the NYU School of Medicine and the New York Harbor VA Hospital.

Baseline address was identified as the address closest to cohort entry date. If an address was not on file prior to cohort entry date, the first address within two years after cohort entry date was accepted. Baseline address was geocoded and spatially joined to the corresponding census tract. PO Box addresses and addresses with missing information (n=1,032,944) and individuals whose addresses were not located in the continental US (n=63,443) were excluded. Patients with first address documented more than two years after cohort entry date and with inconsistent clinic visits history (across different VA sites) were excluded due to higher potential for misclassification of these addresses as baseline addresses (n=884,981). A total of 4,100,588 individuals had available geocoded baseline addresses, which represented approximately 67% of the eligible diabetes-free patients.

2.2 Community Type

Stratification by community type (higher density urban, lower density urban, suburban/small town, and rural) as well as measurement techniques defining community factors in the VADR have been previously described (Hirsch et al. 2020). Briefly, measurement development is stratified by four community types generated at the census tract level using a modification of the Rural-Urban Commuting Area (RUCA) from the US Department of Agriculture developed by the Diabetes LEAD Network (U.S. Department of Agriculture 2020). After collapsing the original RUCA categories into three, census tracts within urbanized areas were then divided into two groups based on land area, resulting in the four

community-type categories that reflect distinct typologies along the rural-urban continuum (McAlexander et al. 2021).

2.3 Primary Exposure: Land Use Environment

LUE, a measure created by the Diabetes LEAD Network collaboration, was used as a proxy for baseline neighborhood walkability (Avramovic et al. 2020; Hirsch et al. 2020). The LUE measure is a factor score from a multiple group confirmatory factor analysis (MGCFA) based on seven components of the built environment measured *circa* 2010 (Table S1): household density, intersection density, street connectivity, average block size, average block length, percent developed land, and establishment density (Meeker et al. 2022). The LUE scores are calculated as a function of the factor loadings that are produced from the MGCFA (Table S2). Calculated among tracts within the same community type designation, a tract with a higher LUE factor score indicates that it is more walkable than a tract with a lower score. The MGCFA fits the model structure within each LEAD community type, thus allowing factor loadings to differ for each community type. As a result of the model being fit within each LEAD community type, we cannot make comparisons across community types. Of the 72,538 census tracts in the contiguous United States, we excluded 323 tracts due to their intersection count or land area equaling 0; thus, we included 72,215 tracts in the analysis. Of the 323 excluded tracts, 42.1% were rural and 52.9% had no LEAD community type designation due to not having a RUCA classification.

Household density measure was available between 1990–2014 annually from the Retail Environment and CardioVascular Disease (RECVD) database interpolated from Longitudinal Tract Data Base (LTDB) containing census data from which we used years 2008 through 2012 American Community Survey (ACS) data (Logan et al. 2014; U.S. Department of Commerce 2020). Percent developed land was available from the National Land Cover Database (NLCD) via the RECVD database from which year 2011 was extracted (Drexel University Urban Health Collaborative 2021; Hirsch et al. 2020). Establishment density measure was taken from the 2010 RECVD NETS-derived variables where all walkable retail was counted except for food and physical activity venues, particularly to avoid endogeneity issues with our food environment construct. Average block size was collected via the 2010 census from the RECVD database as well. Average block length, intersection density, and street connectivity were generated using the 2009 ESRI Vintage Street Data and computed with ArcGIS (ArcGIS by Esri. https://www.esri.com/en-us/home). Five components—average block size, average block length, intersection density, household density, and establishment density—were log-transformed. All seven components were then z-score transformed. In addition, given that larger values of average block length and average block size indicate that a neighborhood is less walkable, we standardized the directionality of these two components, so that these variables would also be indicators of highly walkable areas in a similar direction as the other components. Thus, an increase in any LUE item would indicate development becoming more compact.

2.4 Primary Outcome: Type 2 Diabetes Risk

First onset of T2D was defined as two or more inpatient or outpatient encounters (found in EHR) with T2D ICD-9/10 codes (ICD-9 250; and ICD-10 E11), any prescription of diabetes

medication (excluding metformin or acarbose), or one encounter with diabetes with two or more hemoglobin A1C 6.5% (Avramovic et al. 2020). Vital status for participants was also accessible via VA vital status records and Beneficiary Identification Records Locator Subsystem (BIRLS) files.

2.5 Covariates

2.5.1 Individual-level—Socio-demographic information at the individual-level was collected from EHR data in the VADR cohort for the following variables: age, sex (male, female), race/ethnicity (non-Hispanic white, non-Hispanic black, Hispanic, and other), marital status (married or living with a partner, single), having either a disability or low income, smoking status (current smokers, non-smokers), and access to primary care (distance to nearest VA primary care facility at cohort entry year: within 40 miles vs. not within 40 miles).

2.5.2 Community-level—The Diabetes LEAD Network assigned food environment covariates in the VADR cohort using a network buffer around the population-weighted centroid of a census tract with different scales by community type as follows: 1-mile radius buffer for higher density urban, 2 miles for lower density urban, 6 miles for suburban, and 10 miles for rural neighborhoods (Hirsch et al. 2020; Rummo et al. 2021). Applying community type-specific buffers, we averaged annual values of food environment for the 5 years prior to cohort entry. Relative food environment measures were defined as follows: (1) the percent of total food-serving establishments that were fast-food establishments, calculated as the five-year average number of fast-food restaurants in census tracts relative to all restaurants, and (2) the proportion of total retail food outlets that were supermarkets, also calculated as the five-year average number of supermarkets in census tracts with assigned buffers relative to all food stores. Information on how these measures were created have been published elsewhere (Drexel University Urban Health Collaborative 2021; Hirsch et al. 2021). Briefly, using the RECVD database, we identified food commercial businesses and computed the count of food establishments contained within the census tract-based buffer polygons.

Other population socio-demographic attributes were also measured at the community level. Neighborhood-level race and ethnicity measures (black and Hispanic population percent residing in census tract) were drawn from the RECVD's dataset, originally sourced from LTDB, (Logan et al. 2014) to align all tract geographic boundaries with the year 2010. The value from 2000 was considered baseline neighborhood percent for those entering the cohort prior to 2010 whereas the value at 2010 was used as baseline for those entering the cohort in 2010 and later. This was done due to the limited availability of census data (in years 2000 and 2010). Additionally, a LEAD Network measure of neighborhood socio-economic environment (NSEE) was computed within each community type, composed of summed z-transformed scores of 6 SES variables as follows: % less than HS education + % unemployed + % households earning less than $30k/year + % poverty + % public assistance + % no car. The NSEE variable was taken from 2000 decennial census data and from 2010, final year of the 2006–2010 ACS. Those who entered the cohort before 2010 were assigned

an NSEE score based on 2000 census data. Those who entered the study on or after 2010 were assigned an NSEE score based on 2006–2010 ACS data.

2.6 Statistical Analyses

In total 3,959 veterans were excluded due to missing information in the following variables: age (n=58), sex (n=82), relative environment (n=2,388), and NSEE (n=1,491). Other covariates with missing observations (race/ethnicity, low income or disability flag, marital status, access to VA primary care, and smoking status) were recoded with an unknown category and included in the analyses. We conducted descriptive analyses and then, performed a piecewise exponential (PWE) time-to-event analysis with county-level random effects (accommodating for county-level variation in diabetes ((CDC) 2020; Dwyer-Lindgren et al. 2016; Hipp and Chalise 2015)) and 2-year intervals to improve model efficiency (Austin 2017). We estimated the hazard ratios (HR) for the independent contribution of LUE on incident T2D risk from 2008 until the censoring date (December 31, 2018), accounting for both individual and community-level characteristics, overall and stratified by community types. LUE was categorized into quartiles developed within community-type strata. All models adjusted for age (continuous), sex, race/ethnicity, marital status, low income or disability, smoking status, access to primary care, region (Northeast, Midwest, West, South), NSEE (continuous), percent of black population in neighborhood (continuous), percent of Hispanic population in neighborhood (continuous), and relative measures of food environment (continuous variables for supermarket and fast-food environments). Furthermore, in order to ascertain whether or not the association between LUE and T2D incidence was modified by food environment, we measured the joint effect of LUE (quartile trend to assess dose-response, and by each quartile using dummy variables) and a relative measure of healthy food environment (defined by the median). First, we added a cross-product term between LUE and higher median of relative supermarket environment, and then between LUE and lower median of relative fast-food environment to assess effect modification by food environment on T2D risk. Additional stratified analyses by sex (Table S7) were also conducted given the different prevalence and pathophysiology of T2D noted between males and females in prior studies ((CDC) 2021; Kautzky-Willer et al. 2016).

We additionally conducted various sensitivity analyses. First, due to our large sample size we expect the effect sizes to be small and therefore, we conducted analyses using deciles in addition to quartiles (Table S6). We also restricted to a population with a complete-case analysis with no missing information on any of the covariates (Table S9; n=1,067,249). Second, for a subset of veterans, the EHR address data was obtained within two years after cohort entry date, which made certain assumptions about the veterans having lived in the same location prior to cohort entry. Therefore, we restricted the analyses to patients with data on documented addresses prior to, or on, cohort entry date only (Table S3, S8, S10) with n=2,053,610 individuals. Lastly, we conducted an exploratory analysis without region as a covariate to compare with main models and assess whether any geographic variation was masked (Table S12). All analyses were stratified by community type and implemented using SAS (version 9.4; SAS Institute Inc., Cary, NC).

3. Results

The VADR cohort is composed predominantly of male (92.2%), white (76.3%) veterans, with an average age of 59 years (Table 1). At enrollment, the majority of veterans in our study had access to a VA primary care facility within 40 miles (92.9%), were married or lived with a partner (58.4%), and had either a low income and/or a disability (72.7%). A total of 4,096,629 veteran patients were included in the study with available data on LUE, of which 538,849 (13.2%) developed T2D during the follow-up period.

Nationally, in descriptive analyses, T2D cumulative incidence was lowest (12.8%) among veterans living in the lowest LUE quartile (least walkable), but was similar (13.2–13.3%) among veterans living in the rest of the LUE quartiles (Table 1). This pattern persisted when looking within strata of community types with the exception of suburban/small town, where incidence did not differ by LUE quartile (12.5–12.7%) (Table 2). In terms of distributions for other neighborhood covariates, veterans who developed T2D lived in neighborhoods with similar fast-food restaurants and supermarket availability levels compared to those without incident T2D (Table 1). Veterans with a lower socio-economic status (higher NSEE) were more likely to develop T2D than those who did not. We also explored the distribution of other neighborhood attributes across LUE quartiles. Most notably, in the overall population, veterans who lived in an environment with the highest LUE quartile (greatest walkability) had greater exposure to fast food but similar exposure to supermarket environments compared to those in lower LUE quartiles (Table S4). This pattern was also consistent across most community types, with the exception of higher urban areas where we noted decreasing availability of fast-food establishments and supermarkets the higher the LUE level (Table S5).

In PWE covariate-adjusted analyses, we observed a small protective effect between LUE and incident T2D in suburban/small town and rural communities only, but such an association was not as apparent in higher or lower density urban communities (Table 3). In suburban/small town tracts, there was a dose-response protective effect across LUE quartiles on T2D risk (linear quartile trend test p-value <0.001), which remained in sensitivity analyses using LUE deciles (linear quartile trend test p-value <0.001; Table S6). For instance, the top two highest LUE quartiles in suburban areas were associated with a lower risk (HR: 0.96, 95% CI: 0.95–0.98, and HR: 0.92, 95% CI: 0.91–0.94, respectively) compared to the lowest quartile. In rural communities, the highest quartile had a protective HR of 0.97 (95% CI: 0.96–0.99) compared to the reference group (linear quartile trend test p-value <0.001; Table 3), adjusting for covariates. While there was an inverse relationship between LUE and T2D risk in rural and suburban areas, we observed a marginally small positive association between LUE quartiles and T2D in lower density urban communities (HR: 1.01 (1.00, 1.01); linear quartile trend test p-value <0.001). No associations were found in higher density urban communities (linear quartile trend test p-value=0.317). In stratified models by sex and community type, no interaction effects by sex were observed in any of the community types (p-interaction>0.05; Table S7). In males, the associations as expected were consistent with our findings in the overall VADR population, which is predominantly male. Interestingly, a suggestive protective effect of LUE on T2D risk in higher density urban communities was

observed among female veterans (HR: 0.97 (95% CI: 0.94–1.00), linear quartile trend test p-value=0.064; Table S7).

We then tested the interaction effect between quartiles of LUE and 5-year average supermarket count relative to total retail food outlets in network buffer areas (Table 4). Analyses using dummy variables for LUE quartiles indicated that residing in a neighborhood in the top LUE quartile and above median availability of supermarkets had a protective interaction effect on T2D risk in suburban/small town communities only (Model 1; p-interaction=0.006). For instance, in the higher supermarket availability group, veterans residing in the highest LUE quartile had an 11% [HR: 0.89 (95% CI: 0.87–0.92)] T2D risk reduction, compared to those in the lowest LUE quartile group. Analyses using the trend of quartiled LUE indicated the response was graded across quartiles in both suburban/small town (Model 2; p-interaction=0.001). For instance, in the higher supermarket availability group, for every quartile increase in LUE, veterans who resided in suburban communities had a 4% [HR: 0.96 (95% CI: 0.95–0.97)] lower risk of T2D. Additional analyses using availability of fast-food restaurants as potential effect modifier indicated that LUE's effect on T2D did not vary across fast-food environment groups. Lastly, effect modification results were consistent in the dataset restricted to veterans with a known address before or at cohort entry (Table S8).

In sensitivity analyses restricted to a population with no missing information on any of the covariates (n=1,067,249), the association of LUE on T2D only remained statistically significant in suburban/small town communities (Model 3; Table S9), where the protective association of LUE on T2D was stronger than in main analyses. Compared to the lowest LUE quartile group, those residing in the third and fourth highest quartiles had a 5% [HR: 0.95 (95% CI: 0.91–0.98)] and 10% [HR: 0.90 (95% CI: 0.87–0.94)] lower risk of T2D, respectively, adjusting for covariates (linear quartile trend test p-value <0.001). A similar inverse directionality was still apparent in the rest of the community types with the exception of lower density urban communities (HR: 1.01 (95% CI: 1.00–1.02); linear quartile trend test p-value=0.109). Additional sensitivity analyses were conducted restricting to patients with information on documented addresses prior to, or on, cohort entry date (n=2,053,610; Model 3; Table S10). The protective associations by quartile increase of LUE on incident T2D remained significant, though small in magnitude, in both suburban/small town (HR: 0.97 (95% CI: 0.96–0.98); linear quartile trend test p-value <0.001) and rural communities (HR: 0.99 (95% CI: 0.98–1.00); linear quartile trend test p-value=0.039) and were slightly strengthened in the former communities and weakened in the latter. Interestingly, in both previous multivariable sensitivity analyses, the positive association previously observed in lower density urban communities disappeared. Lastly, analyses performed without region as a covariate, yielded similar estimates than main models (Table S12).

4. Discussion

In this large cohort study of veterans, we found a small protective effect of land use environment, a proxy of neighborhood walkability, on incidence of T2D in less densely populated areas, such as rural and suburban communities. However, no consistent associations were observed in more urban communities. The relative availability of

supermarkets compared to total retail food outlets further strengthened the protective association between land use environment and T2D in suburban communities.

Previous studies on the built environment and neighborhood walkability assessing risk of diabetes have identified inconsistent results (Auchincloss et al. 2009; Booth et al. 2019; Creatore et al. 2016; den Braver et al. 2018; Herrick et al. 2016; Jagai et al. 2020; Kartschmit et al. 2020; Sundquist et al. 2015). While some research found a link between walkability and diabetes (Booth et al. 2013; Christine et al. 2015; Creatore et al. 2016; Müller-Riemenschneider et al. 2013), congruent with our findings, others observed no such association (Herrick et al. 2016; Kartschmit et al. 2020). However, most prior epidemiological research on the built environment and diabetes risk is limited by the use of ecological or cross-sectional designs (Herrick et al. 2016), short-term follow-up (Kartschmit et al. 2020; Sundquist et al. 2015), and lack of stratification by distinct geographical areas. Our study addresses all these points and further examines these associations by community type, underscoring the importance of these neighborhood determinants in suburban and rural areas. It could be that the inconsistent associations observed in prior literature may be in part due to the lack of stratification by community types or research conductive in predominantly urban settings. Our study suggests that improvements in both access to healthier retail outlets, such as supermarkets, and neighborhood walkability may have a protective effect on T2D, particularly in less densely populated areas.

These findings emphasize that potential effects of the built environment on T2D may vary by geographic location in the US. Indeed, we observed stronger associations in rural communities compared to urban communities. Empirical evidence shows health differences between rural and non-rural communities (Anderson et al. 2015; Keel et al. 2017; Krishna et al. 2010), and thus, different communities may benefit differently from built environment changes. It has been hypothesized that the effect of neighborhood walkability on cardiometabolic health may be mediated by improvements in physical activity behaviors (Chandrabose et al. 2019). High levels of walkability components, including household density and walkable destinations, have been linked to higher walking and cycling use, less car dependency, more public transport usage, and lower diabetes prevalence (Glazier et al. 2014). Walkability may function differently in less densely populated areas, where a car is an option and higher walkability may provide an alternative to walk to destinations, as opposed to walkability in urban areas with available public transportation. Inconsistencies in prior literature when evaluating neighborhood walkability and T2D risk may not only stem from lack of consideration of potential differential effects of the built environment across community types, but may also reflect differences in how walkability is operationalized, using either one component or a less comprehensive measure instead of including a multi-factor composite score (Kartschmit et al. 2020). Other studies combined both diabetes type 1 and type 2, making the association more subject to ambiguous interpretation (den Braver et al. 2018). Combining both outcomes could yield results towards the null as type 1 diabetes has a different etiology than type 2diabetes and may be more dependent on genetic factors (Howard 2019; Jerram and Leslie 2017; Malmqvist et al. 2015; Tremblay and Hamet 2019).

In this study, we observed a stronger protective effect of LUE among veterans living in communities with higher relative access to supermarkets, particularly in non-urban

communities. It is possible that less densely populated communties are generally more car-dependent and subject to wider variation in food outlet types and availability. Residing in a supermarket-dense area may thus enhance the protective effects of walkability and lessen the likelihood of developing risk factors for T2D (Leal and Chaix 2011). We previously found that excess availability of fast-food restaurants, which tend to sell energy-dense and nutrient-poor foods, is independently associated with higher risk of T2D (Kanchi et al. 2021). However, we found no evidence that the protective effect of LUE on T2D was stronger in those areas with less fast-food restaurants. While interaction effects by socio-demographic and environmental factors have been previously explored in the association between the built environment and cardiometabolic outcomes yielding inconsistent findings, (Guo et al. 2019; Howell et al. 2019; Jia et al. 2018; Khan et al. 2021; Koohsari et al. 2020; Murillo et al. 2020; Rosso et al. 2021; Sarkar et al. 2017), studies examining the specific joint effects of neighborhood walkability and food environment are scarce. The joint effects of these two specific built environment factors on diabetes markers has been previously examined cross-sectionally, yielding no interaction effects between walkability and food environment (Herrick et al. 2016). The latter study added interaction terms between walkability and food environment on the outcome 'high risk for diabetes' based on levels of BMI, cholesterol, blood pressure, and glucose, in lieu of a diabetes diagnosis, and their walkability exposure was operationalized as a WalkScore measure (Herrick et al. 2016). Other researchers have combined both healthy food and physically active environments as exposure and/or assessed interaction effects with socio-economic factors yielding inconsistent results (Auchincloss et al. 2009; Christine et al. 2015; Fan et al. 2019; Fazli et al. 2020; Gebreab et al. 2017). To our knowledge, our study is the first including an interaction effect of a comprehensive measure for land use environment and food environment using a large longitudinal cohort.

We also noted that, by the end of the study, the incidence of T2D in our cohort was higher than that in the general US adult population, a pattern which has been previously reported (Miller et al. 2004; U.S. Department of Veterans Affairs 2019) and may in part reflect that the cohort is, on average, older, male and of lower income than the national profile. Prior reseach has identified a stronger protective effect of neighborhood walkability on T2D in males compared to women (Müller-Riemenschneider et al. 2013), consistent with our findings in a predominantly male population. Further longitudinal studies should address potential mediation pathways, by adding lipid profiling and additional cardiometabolic biomarkers. Research should also be conducted examining how built environment interventions may encourage less car dependency and more outdoor walking in different community types.

Our study has several limitations. Potential misclassification of exposure could have occurred, as patients may have moved during the follow-up period and there is potential for neighborhood self-selection bias. We used a baseline LUE measure only due to the unavailability of road network data (including block length, intersection density, and street connectivity) across years of follow-up. While neighborhood characteristics were assigned using patients' baseline address irrespective of moving at a later time, other studies have identified that, in general, people tend to move to neighborhoods with similar characteristics (Auchincloss et al. 2009). We expect that participants move to areas alike and thus, expect that neighborhood walkability remains stable over time as previously indicated by other

cohorts (Creatore et al. 2016). Also, by capturing the exposure prior to the outcome we resolved temporality biases. Future studies incorporating a longitudinal walkability measure and mediation analyses by outdoor walking and dietary behaviors are warranted. Some covariates had missing information but we conducted sensitivity analyses restricting to non-missing covariates and a consistent protective pattern was observed for suburban/small town communities, our strongest finding. We also report that no major differences were observed in the distribution of covariates in the complete-case population and the population with missing covariates (Table S11). The study findings should be interpreted with caution as the veteran population, composed of predominantly white adult males, is not generalizable to the rest of the US population. The study also relies on EHR data and measurement error may be possible. We anticipate that missing data on diabetes encounters will be largely non-differential in relation to LUE, thus results may be biased towards the null.

On the other hand, this study has several strengths. Participants' addresses were extracted from the VA database at the individual level and a comprehensive neighborhood walkability construct (LUE) was generated. We measured access to a healthy food environment at the census tract level by characterizing fast-food and supermarket areas, which constitutes a more comprehensive relative measure of food outlets as it accounts for various types of food retail stores (healthy and unhealthy), unlike most previous studies (Caspi et al. 2012). Additionally, this study is large in sample size, adjusts for both individual and neighborhood-level covariates, and is longitudinal in design.

Our study findings suggest a possible impact of built environment factors on T2D risk that is differential across community types in the US. This warrants a further assessment of interventions accompanied by improvements in both walkable and healthy food environment spaces in order to evaluate potential protective effects on cardiometabolic health in the population, particularly in the less densely populated areas. Policies may be substantiated in rural and suburban areas where stakeholders may advocate for resource allocation facilitating urban health interventions to prevent T2D.

5. Conclusion

In a study of predominantly male veterans, we found that the built environment may particularly influence T2D incidence in rural and suburban communities. Food environment may be a potential effect modifier of the association between land use environment and T2D.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

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Table 1.

VADR Characteristics by Incident Type 2 Diabetes Status.[a]

Characteristics	Cohort Total (N=4,096,629)	No Diabetes (n=3,557,780)	Diabetes[b] (n=538,849)
Age at Enrollment, Mean (SD)	59.4 (17.2)	58.9 (17.8)	62.5 (12.3)
Sex, N (%)			
Male	3,776,086 (92.2)	3,263,646 (91.7)	512,440 (95.1)
Female	320,543 (7.8)	294,134 (8.3)	26,409 (4.9)
Race/Ethnicity, N (%)			
Non-Hispanic White	2,781,184 (76.3)	2,421,878 (76.9)	359,306 (72.6)
Non-Hispanic Black	584,206 (16.0)	485,284 (15.4)	98,922 (20.0)
Hispanic	188,909 (5.2)	164,701 (5.2)	24,208 (4.9)
Other[c]	91,502 (2.5)	78,754 (2.5)	12,756 (2.6)
Marital Status, N (%)			
Married or Living with Partner	2,211,598 (58.4)	1,920,624 (58.2)	290,974 (59.7)
Single	1,577,148 (41.6)	1,380,781 (41.8)	196,367 (40.3)
Low Income or Disability Flag, N (%)			
No	1,099,928 (27.3)	972,978 (27.8)	126,950 (23.8)
Yes	2,928,351 (72.7)	2,521,468 (72.2)	406,883 (76.2)
Smoking Status, N (%)			
Non-Smoker	901,977 (59.7)	793,075 (59.8)	108,902 (58.9)
Current Smoker	609,894 (40.3)	533,768 (40.2)	76,126 (41.1)
Access to Primary Care, N (%)			
VA PC within 40 miles	3,146,710 (92.9)	2,731,436 (92.9)	415,274 (92.8)
No VA PC within 40 miles	240,131 (7.1)	208,068 (7.1)	32,063 (7.2)
Community Level			
Land Use Environment, N (%)			
Quartile 1	1,023,295 (25.0)	892,105 (87.2)	131,190 (12.8)
Quartile 2	1,023,462 (25.0)	887,834 (86.8)	135,628 (13.3)
Quartile 3	1,025,248 (25.0)	889,792 (86.8)	135,456 (13.2)
Quartile 4	1,024,624 (25.0)	888,049 (86.7)	136,575 (13.3)

Characteristics	Cohort Total (N=4,096,629)	No Diabetes (n=3,557,780)	Diabetes[b] (n=538,849)
Buffer Supermarket Tract Relative 5-Yr Average, Mean (SD)[d]	0.11 (0.1)	0.11 (0.1)	0.11 (0.1)
Buffer Fast Food Tract Relative 5-Yr Average, Mean (SD)[d]	0.30 (0.1)	0.30 (0.1)	0.30 (0.1)
NSEE, Mean (SD)[e]	16.1 (9.6)	16.0 (9.6)	16.8 (9.9)
Region, N (%)			
Northeast	620,432 (15.1)	542,647 (15.3)	77,785 (14.4)
Midwest	970,923 (23.7)	841,445 (23.7)	129,478 (24.0)
West	787,052 (19.2)	691,120 (19.4)	95,932 (17.8)
South	1,718,222 (41.9)	1,482,568 (41.7)	235,654 (43.7)
Community Type, N (%)			
Higher Density Urban	478,097 (11.7)	409,869 (11.5)	68,228 (12.7)
Lower Density Urban	1,508,041 (36.8)	1,310,605 (36.8)	197,436 (36.6)
Suburban/Small Town	918,068 (22.4)	802,596 (22.6)	115,472 (21.4)
Rural	1,192,423 (29.1)	1,034,710 (29.1)	157,713 (29.3)
Black Population Percent in Neighborhood, Mean (SD)	12.7 (21.3)	12.4 (20.9)	14.7 (23.5)
Hispanic Population Percent in Neighborhood, Mean (SD)	10.2 (16.0)	10.2 (15.9)	10.2 (16.2)

[a]The dataset excluded observations with unavailable data on land use environment, certain states and those observations with addresses provided 2 years after cohort entry date for those patients with more than one physical station visit in their clinical history, but the stations are in the same or different state as the patient's address (n=1,981,430). After restricting the dataset, race/ethnicity had 450,820 missings, low income or disability flag had 68,350 missings, marital status variable had 307,883 missings, access to VA primary care variable had 709,788 missings, and smoking status had 2,584,758 missings.

[b]Incident type 2 diabetes between 2008 and 2018. No incident type 2 diabetes include non-cases, lost to follow up, or deaths.

[c]Other category includes Non-Hispanic Asian, Native American or Alaska Native, Native Hawaiian or other Pacific Islander.

[d]Buffers were assigned for each participant based on community type: higher density urban 1-mile walking buffer; lower density urban 2-mile driving buffer; suburban/small town 6-mile driving buffer; and a 10-mile driving buffer in rural areas.

[e]The neighborhood social and economic environment (NSEE) measure is a community-type stratified, z-score sum of 6 US Census-derived variables, with sums scaled between 0 and 100. A tract with a higher NSEE z-score sum indicates more socio-economic disadvantage compared to a tract with a low z-score sum. 6 Census variables used to construct this measure include: % of males and females with less than a high school education, % of males and females unemployed, % of households earning less than $30,000 per year, % of households in poverty, % of households on public assistance, and % of households with no cars.

Table 2.

Type 2 Diabetes by Land Use Environment Quartiles and Stratified by Community Type.[a]

Community Type	Diabetes Status	Land Use Environment Quartiles				
		LUE Q1 N (%)	LUE Q2 N (%)	LUE Q3 N (%)	LUE Q4 N (%)	
Higher Density Urban						
	No	103,050 (86.4)	102,644 (85.8)	101,978 (85.4)	102,197 (85.4)	
	Yes	16,241 (13.6)	17,064 (14.3)	17,462 (14.6)	17,461 (14.6)	
Lower Density Urban						
	No	328,563 (87.2)	328,100 (87.1)	327,613 (86.9)	326,329 (86.5)	
	Yes	48,255 (12.8)	48,804 (13.0)	49,250 (13.1)	51,127 (13.6)	
Suburban/Small town						
	No	200,542 (87.5)	200,522 (87.4)	200,831 (87.5)	200,701 (87.3)	
	Yes	28,567 (12.5)	29,038 (12.7)	28,733 (12.5)	29,134 (12.7)	
Rural						
	No	259,354 (87.2)	257,598 (86.4)	258,284 (86.6)	259,474 (86.9)	
	Yes	38,155 (12.8)	40,528 (13.6)	39,919 (13.4)	39,111 (13.1)	

[a]Land Use Environment quartiles shown are based on quartiles stratified by each community type.

Table 4.

Interaction between LUE and Food Environment in PWE Analyses with Land Use Environment as Predictor of Type 2 Diabetes Incidence (n=4,096,629).

	Relative Supermarkets					Relative Fast-Food Restaurants				
LUE	Supermarket Food Environment ≤ Median (n=2,048,312)		Supermarket Food Environment > Median (n=2,048,317)		p-interaction	Fast-Food Environment ≤ Median (n=2,048,314)		Fast-Food Environment > Median (n=2,048,315)		p-interaction
	n	HR (95% CI)	n	HR (95% CI)		n	HR (95% CI)	n	HR (95% CI)	
Higher density urban										
Model 1 Q1	307,493	ref.	170,604	ref.	ref.	326,964	ref.	151,133	ref.	ref.
Q2		1.014 (0.986, 1.042)		1.019 (0.981, 1.057)	0.810		0.998 (0.971, 1.026)		1.013 (0.973, 1.053)	0.226
Q3		0.993 (0.963, 1.022)		1.019 (0.980, 1.058)	0.213		0.991 (0.963, 1.020)		1.003 (0.963, 1.044)	0.036 *
Q4		0.984 (0.952, 1.016)		1.002 (0.961, 1.044)	0.752		0.978 (0.948, 1.009)		0.972 (0.930, 1.016)	0.168
Model 2 Trend		0.993 (0.983, 1.004)		0.999 (0.986, 1.012)	0.961		0.993 (0.983, 1.003)		0.990 (0.977, 1.004)	0.290
Lower density urban										
Model 1 Q1	830,146	ref.	677,895	ref.	ref.	731,146	ref.	776,895	ref.	ref.
Q2		0.986 (0.968, 1.003)		1.010 (0.991, 1.030)	0.050		0.977 (0.959, 0.996) *		1.007 (0.989, 1.026)	<0.001 *
Q3		1.010 (0.993, 1.030)		0.990 (0.971, 1.011)	0.064		1.002 (0.983, 1.023)		1.000 (0.981, 1.019)	0.130
Q4		1.030 (1.010, 1.051) *		1.019 (0.997, 1.041)	0.800		1.010 (0.988, 1.031)		1.040 (1.019, 1.060) *	0.204
Model 2 Trend		1.008 (1.002, 1.015) *		1.004 (0.997, 1.011)	0.524		1.005 (0.999, 1.012)		1.010 (1.004, 1.017) *	0.543
Suburban/small town										
Model 1 Q1	441,592	ref.	476,476	ref.	ref.	380,336	ref.	537,732	ref.	ref.
Q2		0.992 (0.967, 1.018)		0.971 (0.948, 0.994) *	0.778		0.989 (0.962, 1.017)		1.006 (0.983, 1.029)	0.826
Q3		0.982 (0.957, 1.008)		0.930 (0.908, 0.953) *	0.123		0.953 (0.927, 0.979) *		0.971 (0.949, 0.994) *	0.399

		Relative Supermarkets					Relative Fast-Food Restaurants				
		Supermarket Food Environment ≤ Median (n=2,048,312)		Supermarket Food Environment > Median (n=2,048,317)			Fast-Food Environment ≤ Median (n=2,048,314)		Fast-Food Environment > Median (n=2,048,315)		
LUE		HR (95% CI)	n	HR (95% CI)	n	p-interaction	HR (95% CI)	n	HR (95% CI)	n	p-interaction
	Q4	0.959 (0.933, 0.986)*		0.893 (0.869, 0.918)*		0.006*	0.910 (0.883, 0.937)*		0.928 (0.904, 0.952)*		0.595
Model 2	Trend	0.986 (0.977, 0.995)*		0.960 (0.952, 0.968)*		0.001*	0.970 (0.961, 0.980)*		0.976 (0.968, 0.984)*		0.684
Rural											
Model 1	Q1	ref.	469,081	ref.	723,342	ref.	ref.	609,868	ref.	582,555	ref.
	Q2	1.035 (1.008, 1.062)*		1.031 (1.010, 1.052)*		0.982	1.023 (1.000, 1.047)*		1.022 (0.999, 1.045)		0.199
	Q3	1.044 (1.016, 1.073)*		1.019 (0.998, 1.041)		0.014*	1.030 (1.006, 1.054)*		1.010 (0.987, 1.033)		0.018*
	Q4	0.985 (0.959, 1.013)		0.985 (0.964, 1.006)		0.425	0.980 (0.957, 1.004)		0.978 (0.955, 1.001)		0.517
Model 2	Trend	0.996 (0.988, 1.005)		0.993 (0.987, 1.000)		0.882	0.995 (0.987, 1.002)		0.992 (0.985, 0.999)*		0.768

*
P <0.05.

Piece-wise exponential models with 2 year intervals adjusting for individual-level variables age, sex, race/ethnicity, low income or disability, marital status, smoking status, access to primary care, and region and community-level variables NSEE, food environment, Hispanic population percent living in census tract, black population percent living in census tract. Census tract wide 5-year average supermarkets count relative to total retail food outlets and average fast food restaurants count relative to total fast-food restaurants count relative to total fast-food establishments in network buffer areas around population-based centroid of a tract was used to adjust for food environment in models assessing interaction, and in stratified models when applicable (adjusting for supermarkets in stratified models by fast-food environment and adjusting for fast-food environment in stratified models by supermarket environment). Buffers were assigned for each participant based on community type: 1-mile walking buffer in higher density urban areas, 2-mile driving buffer in lower density urban areas, a 6-mile driving buffer in suburban/small towns, and a 10-mile driving buffer in rural areas. All models were clustered by county. Interaction was defined as the cross-product of LUE and food environment. Model 1 shows the joint effects between quartile LUE and dichotomized (by the median) 5-year average supermarket count relative to total retail food outlets in network buffer areas. Model 2 uses quartile LUE as trend and dichotomized supermarket count relative to total retail food outlets in network buffer areas. The same procedure was used to assess interaction between higher levels of LUE and lower fast-food environment level.