

Article

Walkability, Land Use and Physical Activity

Yehua Dennis Wei ^{1,*}, Weiye Xiao ¹, Ming Wen ² and Ran Wei ¹

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¹ Department of Geography, University of Utah, Salt Lake City, UT 84112, USA; weiye.xiao@utah.edu (W.X.); ran.wei@utah.edu (R.W.)

² Department of Sociology, University of Utah, Salt Lake City, UT 84112, USA; ming.wen@soc.utah.edu

* Correspondence: wei@geog.utah.edu; Tel.: +86-801-585-0545; Fax: +86-801-585-8218

Abstract: Physical activity (PA) promotes healthy life and contributes to sustainable development. In this paper, we rely on the Utah Household Travel Survey data and analyze the determinants of PA in terms of neighborhood land use, accessibility to transportation, and socio-demographic status in Salt Lake County, Utah, United States using four-component walkability indices at various geographic scales. We find that PA is associated with neighborhood land use and social demographic status, including the compact design of the neighborhood. The results also indicate that land use mix is insignificant, and that current neighborhood design only supports people's 20-min walk. The spatial lag model reveals significant spatial autocorrelation of PA but the barely improved R^2 validates the dominant effect of neighborhood land use and social demographic status on people's walking behavior.

Keywords: walkability; land use; physical activity; spatial regression; Salt Lake County

1. Introduction

The United States is troubled by a high obesity rate, although the rate at which it is increasing appears to have slowed [1]. The same trend is evident in Salt Lake County in which approximately 25.4% of adults are obese, and childhood obesity rates are also on the rise [2]. High obesity prevalence has clearly become a legitimate public health concern, motivating researchers to examine the determinants of obesity problems. Given that physical inactivity is widely considered as a major risk factor for overweight and obesity [3,4], increasing physical activity (PA) would help to promote citizens' health and contribute to sustainable development.

A large body of literature has emerged to address the effects of social environment and urban form on PA. Evidence shows that physical inactivity results from the synthesis of urban amenity, socio-demographic status, personal preference, and genetic factors [5]. Density, diversity and accessibility are driving factors of PA, and residents living in neighborhoods characterized by higher residential density and land-use diversity tend to walk more [6]. Mixed land use, higher network connectivity and denser residential space can help to improve neighborhood walkability [7]. PA is also associated with neighborhood social and environmental factors, such as socio-demographic status, transportation, land-use pattern, and neighborhood design [8–13].

This study first maps the spatial distribution of walking behavior and land-use factors and then explores the spatial autocorrelation and clustering of walking behavior. Second, we test the validity of four land use measures to predict walking behavior at different geographical scales. Last, we examine the relationships between walking behavior and neighborhood social and physical characteristics, including transportation and socio-demographic status.

2. Literature Review

2.1. Physical Activity: Benefits and Measurements

PA is defined as any bodily movement produced by skeletal muscles that results in energy expenditure [14]. Regular PA is regarded as an important component of a healthy lifestyle [15]. The benefits of PA are well documented, and it is widely recognized that increasing PA can help to prevent excessive weight gain [12,16–19], improve disease control [15,20,21], reduce the symptoms of depression [22], and more generally, enhance health. The American College of Sports Medicine and the Centers for Disease Control and Prevention recommended 30-min of moderate or vigorous PA (e.g., walking and jogging) per day for five days a week for 18–65 year-old-healthy adults [23].

Developing a reliable tool to quantify PA is a priority. A wide range of methods in the form of subjective or objective tools are available to capture PA. The most commonly used tools are the subjective tools like surveys and questionnaires. Baecke *et al.* [24] classify habitual PA into 29 items, which concern occupation, movement, and PA during leisure time, including sports and sleeping habits. By evaluating over 10 questionnaires about PA, Jacobs *et al.* [25] call for a more comprehensive questionnaire about different kinds of PA. The “last 7 day recall”, which includes questions about people’s PA participation in the last seven days, proves to be suitable for PA research [26]. There are many resources for survey-based and self-reported measurement of PA, some of which are published and accessible online [27]. Compared with subjective measures, objective measures are more precise and reliable [28]. However, the high cost of the techniques entailed in collecting objective PA data impedes its wide application. Accelerometer is one of the widely used objective tools in PA research and performs well [29–32]. Using both objective and subjective PA measurement tools is encouraged in future PA work [31].

2.2. Determinants of PA

PA participation in the US is not adequate, and one in three adults and four in five adolescents do not meet levels of PA recommended by public health guidelines [14,32–34]. The etiology of individuals’ participation in PA, including socio-demographic status and individual characteristics, has drawn much attention. Age is one of the most examined demographic factors. Teenagers’ participation in PA declines drastically as they grow up. PA participation tends to be stable in young and middle-aged adulthood, then increases a little after middle-age adulthood and declines in old age [14,35–37]. Gender is another important PA correlate, although the observed pattern has not been always consistent [34,38–41]. PA is also linked to family structure at least among children [42]. Finally, PA prevalence is higher among Caucasians than African-American and Hispanics [4,43].

The relationship between urban form and travel behavior is a key concern of urban planning [44]. Among various urban forms, mixed land use and public transit are found to facilitate residents’ travel-based PA [45]. The sprawl index, a linear combination of 22 land-use variables, seems to be associated with PA, as people living in sprawling metropolitan areas tend to walk less and weigh more [46]. High levels of PA are detected in the neighborhoods with highly mixed land use, high density and great accessibility to work opportunity [47–49]. Street design features such as street connectivity, street safety, sidewalk and crosswalk in the neighborhoods are also examined with results showing that people walk more in a well-connected and safe street [47–49]. Furthermore, neighborhood amenities like access to parks are also linked to PA, with park amenity characteristics appearing to be better determinants of PA than park accessibility [50,51].

2.3. Walkability and Land-Use

Walking is recommended as one of the best forms of moderate-vigorous physical activities. Compared to vigorous PA, walking is suitable for people at all ages [17,23]. In order to promote walkability, the “5D” theory, which includes population density, pedestrian-friendly design, diversity of destinations, destination accessibility, and distance to transit, is proposed as a measure of urban

form, and walkability increases with the increase in the values of the “5D” variables [9,47,52–54]. The original walkability index is proposed to include three variables: street connectivity, net residential density, and land use mix, which respectively describes the pedestrian-friendly design, population density and diversity of neighborhood land use [11]. The retail floor area ratio is then added to achieve a more favorable result [12]. This four-component walkability index is used in many studies concerning walkability [55–61]. However, the application of the four-component walkability index is still limited. A context-specific walkability index is proposed by Mayne *et al.* [58] and Christian *et al.* [10]. Mayne *et al.* [58] test the validity of the context-specific walkability index and find that the context-specific walkability index can maintain about 90% of the full walkability index. Likewise, a three-component walkability index developed based on a PA study in Sweden stresses that future policies concerning the built environment should be based on context-specific factors [62].

Among these four components of walkability index, land-use mix is the most emphasized. For instance, by testing the effect of multi-category land-use mix on obesity, Brown *et al.* [7] argue that walkable land-use relates to healthy weight. As a component of walkability index, varying combination of land-use mix is also suggested to affect the strength of the relationship with different types of walking [10]. Geographical scale is also a key element in calculating land-use mix [63,64]. However, land-use mix is not always a significant indicator of walkability [10], and the performance of land-use mix depends on the types of trips and study areas [10,58].

In summary, two limitations in the current literature are noteworthy. First, little work has been carried out to take spatial autocorrelation into consideration and to employ spatial regression models. Both these methods are important because walking is a spatial behavior with spatial clustering and variation. Second, the effect of context-specific walkability indices constructed on various geographical scales is less studied and remains largely unknown.

3. Data and Methodology

3.1. Study Area and Data Source

The validity of land use and walkability indices is evaluated in the Salt Lake County, which covers over 2000 km² and has a population of about 1 million in 2010. This research primarily relies on the Utah Household Travel Survey (UHS), which was a travel diary-based survey conducted in 2012 by multiple state government agencies and organizations, including Wasatch Front Regional Council, Utah Department of Transportation, and Utah Transit Authorities. This survey took three days to record 101,404 biking, driving and walking trips taken by 27,064 individuals living in 9155 households across the State of Utah. About 2800 households in Salt Lake County participated in this survey [65]. However, people in some households did not report their walking trips or their walking behavior. After checking this data, 158 households in Salt Lake County with complete information were selected as samples in this research. The spatial distribution of these 158 households is presented in Figure 1. The spatial data, including locations of public facilities, road network, and bus and light rail stations, come from the Utah Automatic Geographic Reference Center. Additionally, the land use data at the parcel level is from Salt Lake County 2012 tax assessor’s Computer assisted mass appraised (CAMA) data.

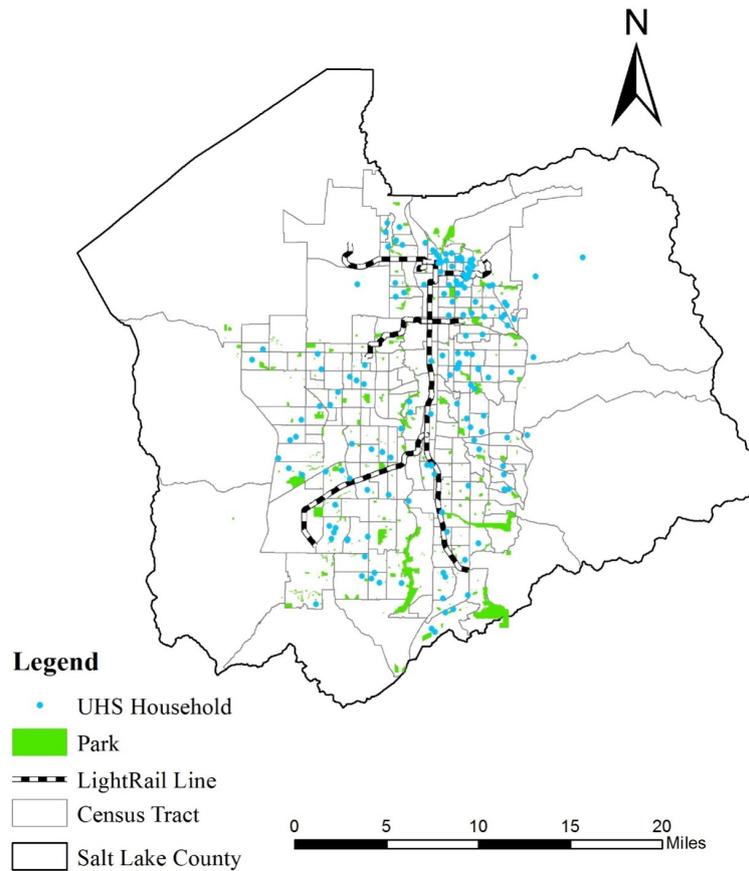


Figure 1. Study area.

3.2. Measures

According to previous research on PA [8,10,11], the average of an individual’s walking minutes is a proper dependent variable to measure walking behavior. Since it is a trip-level data and the neighborhood environment is measured at household level, the data are aggregated into household level.

With the records of people’s walking trips, the frequency of walking every week and the household size, the average value of people’s walking minutes for each household can be estimated and used as the dependent variable. Due to the fact that the dependent variable is skewed, the natural log transformation is used to achieve a continuous dependent variable with approximate normal distribution. We consider the independent variables as the accessibility to transportation, amenities, socio-demographic conditions (household level), land use, and walkability index (Table 1). Transportation, amenities, land use and walkability index are calculated using ArcGIS, the most popular commercial GIS software, and Python, an open-source programming language.

Table 1. Definition of variables.

Dependent Variables	Description
<i>PA</i>	Ln (Average time of people’s walking trips)
Predictor Variables	Description
<i>Accessibility (AS)</i>	Ln (Distance to closest bus station) Ln (Distance to closest light rail station)
<i>Amenity (A)</i>	Ln (Distance to closest park) Ln (Distance to closest worship)

Table 1. Cont.

Dependent Variables	Description
<i>Socio-demographic Conditions (SC)</i>	Average Age
	Average Education level
	Vehicles per person
	Percentage of adult workers
	Average Household Income (4-caterogy data)
<i>Land use and Walkability index</i>	Dwelling Density
	Street Connectivity
	Land-Use Mix
	Retail Floor Area Ratio

3.3. Statistical Methods

Ordinary least squares (OLS) modeling is performed to examine the relationship between average time of walking trips and walkability index, transportation, amenities, and socio-demographic status. However, since previous studies have shown that people's walking minutes largely depend on neighborhood environment [11,47], walking minutes are likely to be spatially autocorrelated. Spatial autocorrelation test is also conducted, which confirm the existence of such spatial autocorrelation. The Moran's I is 0.26 with statistical significance. Given that ignoring the spatial autocorrelation could cause biased and inconsistent estimates for the regression coefficients [66], spatial lag model is employed to incorporate the spatial autocorrelation of walking time by introducing a spatially lagged dependent variable in the regression equation as follows:

$$y = \rho \times W \times y + \beta \times x + \varepsilon \quad (1)$$

y is the walking time to be regressed, ρ is the spatial autoregressive coefficient, and W is the spatial weight matrix defining neighbors for each location. In this case, the point based method, Delaunay triangulation is employed to define the spatial weight matrix W . According to the method, the circumcircle of any triangle contains no point in its interior [67]. If a leg of a Delaunay triangle connects observation i and j , it sets the elements in the unweighted spatial weight matrix $D(i, j) = 1$ [68]. This will naturally result in a symmetric matrix. With a row-standardized spatial weight matrix, $W \times y$ is the average of the neighbors' walk minutes, which is usually referred to a spatially lagged dependent variable. x and β are the independent variables and their corresponding coefficients. ρ is the coefficient for the spatially lagged dependent variable. ε is a vector of the error term. In this model, the spatial autocorrelation is measured as an independent variable in the regression model and the spatial regression model can get better model performance and predictive accuracy [69].

4. Walkability Index and PA

Walkability is initially operationalized as a composite of four environmental attributes within the neighborhood area, which is defined by the road network buffer with specified bandwidth:

Dwelling density: Residential parcels within the buffer area are selected and then the total area of the selected parcels and the total number of dwelling units are summarized. Dwelling density is finally calculated by dividing the number of dwelling units by the total area of residential parcels within the neighborhood. The high dwelling density can not only improve the accessibility of complementary activities, but also compress the living space [56].

Street connectivity: Connectivity is measured by the number of intersections per square kilometer within the network buffer. Only the intersections with three or more unique intersecting streets are included in the street connectivity calculation.

Land-use mix: Land-use mix is used to evaluate the evenness in the distribution of land use. If the land use is evenly distributed in the network buffer, the value of land use mix would be 1. If there is

only one type of land use in the network buffer, the value would be 0. The method to calculate land use mix and the relationship between land use mix and walkability is well discussed by Christian *et al.* [10]. The land use mix described in this paper is calculated with four land use types: residential, commercial, industrial, and recreational.

Retail floor area ratio: the parcels in commercial use are used to calculate the retail floor area ratio. Salt Lake County 2012 tax assessor's computer-assisted mass appraisal (CAMA) database provides the ground floor area for each parcel. Retail floor area ratio is the total ground floor area divided by the total area in household network buffer. High retail floor area ratio means more optional destinations for shopping and more local employed opportunities within the walking distance [56]. The parking space would be compressed as well and walking is more encouraged.

While selecting a proper geographic scale is discussed in the previous studies, little thought is given regarding how or why these geographic scales should be selected to define neighborhood areas [70]. The importance of geographical scale and multilevel approaches are also emphasized in PA research [6,71,72]. Yamada *et al.* [63] have employed three different geographical scales, 1-km network buffer, block group, and census tract, to demonstrate that different geographical scales could lead to different walkability measures. Moudon *et al.* have employed four scales of neighborhood to identify walkable neighborhoods [73]. Schlossberg and Brown have also studied the relationship between walkability indicators and transit-oriented development at two geographical scales (0.25 mile and 0.5 mile) [74]. Since this research aims to create a context-specific walkability index, multi-scale tests on the performance of these four components are conducted to explain PA. A variety of bandwidths is used to buffer the road network to define neighborhood area, including 400 m (5-min walk), 600 m (10-min walk), 800 m (10-min walk), 1000 m, 1200 m (15-min walk), 1500 m, 1600 m (20-min walk), and 1700 m. The OLS model is used to examine the relationship between walkability index and walking minutes with different geographical scales. The results are shown in Figures 2 and 3.

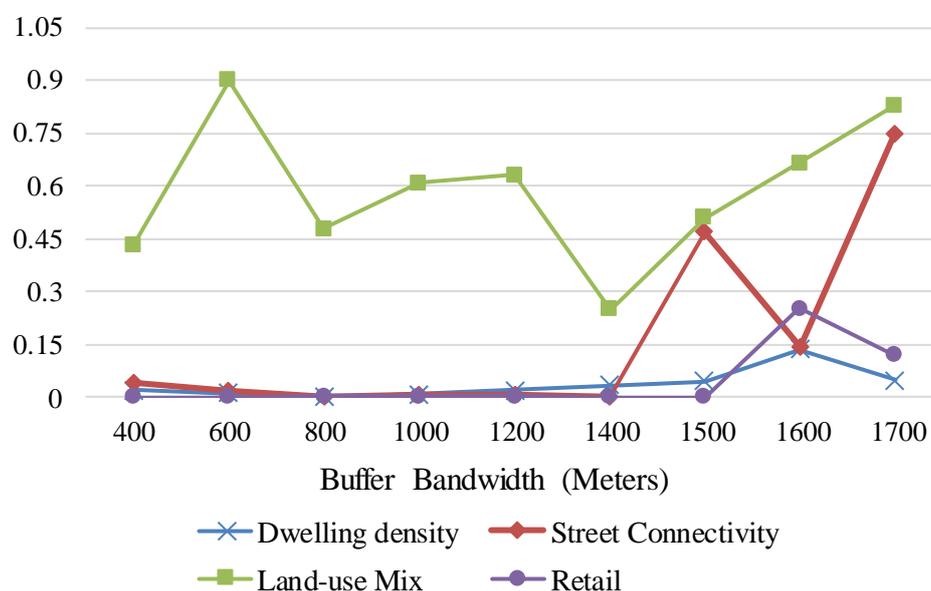


Figure 2. The result of multi-scale test (p -value).

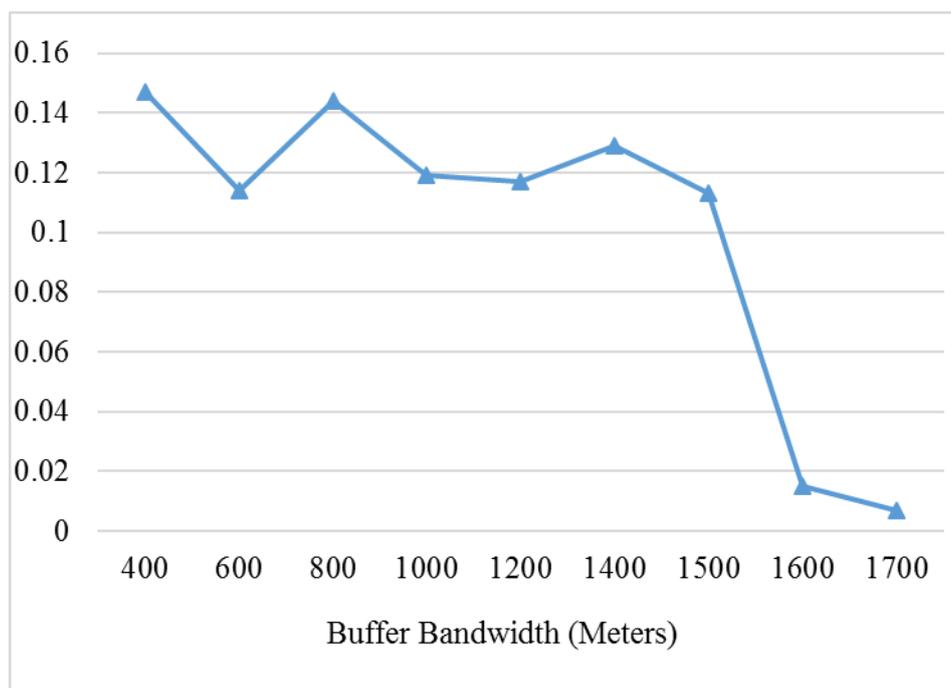


Figure 3. The result of multi-scale test (R^2).

Figure 2 shows the significance of each component. The significance of dwelling density, street connectivity and retail floor area ratio decrease dramatically when the bandwidth of the network buffer reaches about 1600 m. The R^2 also experiences a rapid decline around 1600 m, implying that the neighborhood environments, including street connectivity, the commercial land use, and population density, do not affect people's walking trips beyond 1600 m. In other words, the neighborhood environments only affect walk trips within 20-min walking distance in Salt Lake County, and longer trips usually depend on some other factors, such as self-selection. In fact, according to Root's research on geographic scale, in many U.S. urban areas, people routinely travel 5 to 10 miles to carry out many daily activities, such as shopping, taking children to school, or exercising [75]. According to the trip records, the average walking time is about half an hour for each person per day. Comparatively, Salt Lake County is now at a low walkability level and the future development of neighborhood environment is promising to improve walkability.

Another interesting point here is that the land use mix is not significant at any geographical level. Figure 4 shows the spatial clusters of physical activities in Salt Lake County using the local indicator of spatial autocorrelation (LISA). The spatial clusters of land use mix are displayed in Figure 5. Clearly, the clusters of high physical activities are not consistent with those of large land use mix, suggesting that land use mix is not a good indicator of PA or the relationship between land use mix and PA is not linear. Research in Salt Lake County and Australia reveal that the even mixture of land use does not necessarily lead to better walkability. The performance of land use mix is largely affected by the land use category, the type of walking, and the study area [8,10].

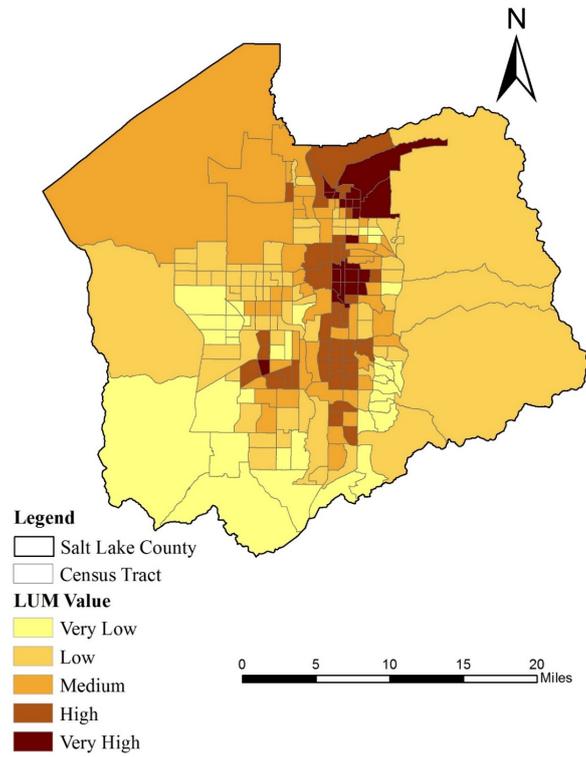


Figure 4. Spatial distribution of land use mix (LUM) in Salt Lake County.

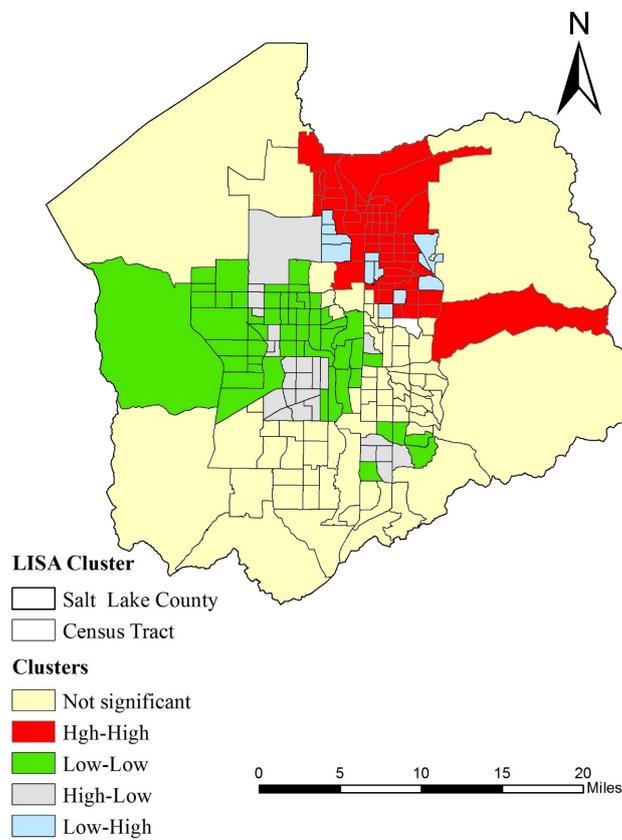


Figure 5. Spatial clusters of PA in Salt Lake County.

5. Result of Statistical and Spatial Analyses

Based on the results of the performance of walkability index under different bandwidths, the neighborhood is defined as the 800-m road network buffer. The OLS linear regression model is used to examine the determinants of the PA in Salt Lake County and the results are shown in Table 2. The results of variance inflation factor (VIF) test for all the variables are all below 5, indicating that there is no alarming multi-collinearity issue. The adjusted R^2 is 0.453 while the p-value for F-statistics is significant, suggesting the great fitness of this regression model.

Table 2. Ordinary least squares (OLS) regression results.

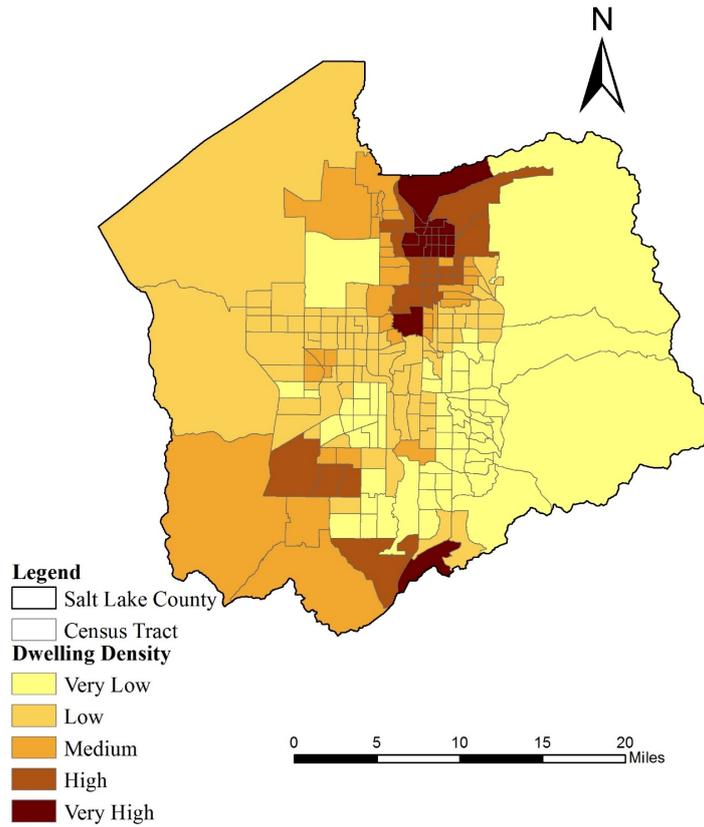
Variable	Coefficient	p-Value
Accessibility		
<i>Distance to bus stop</i>	−0.037	0.670
<i>Distance to light rail stop</i>	−0.061	0.685
Amenity		
<i>Distance to park</i>	−0.152	0.191
<i>Distance to worship</i>	0.232	0.04
Socio-demographic Conditions		
<i>Average AGE</i>	0.005	0.067
<i>Average education level</i>	0.735	0.0003
<i>Vehicles per person</i>	−0.146	0.181
<i>Percentage of adult worker</i>	0.232	0.152
<i>Household income</i>	−0.037	0.116
Land use		
<i>Dwelling density</i>	1381	0.021
<i>Street connectivity</i>	−3198	0.187
<i>Land use mix</i>	−0.127	0.316
<i>Retail floor area</i>	12.98	0.027
Assessment		
R^2	0.4452	

According to Figure 3, land use factors can explain about 15% of the variance of the dependent variables, so the land use indicators play a vital role in explaining people's walking behavior. Among these four factors, dwelling density and retail floor area ratio show great significance and both contribute positively to PA. Higher population density indicates more walkable communities. The commercial land use is also a key element in promoting walkability and thus the compact design of the commercial land use could help to improve neighborhood walkability.

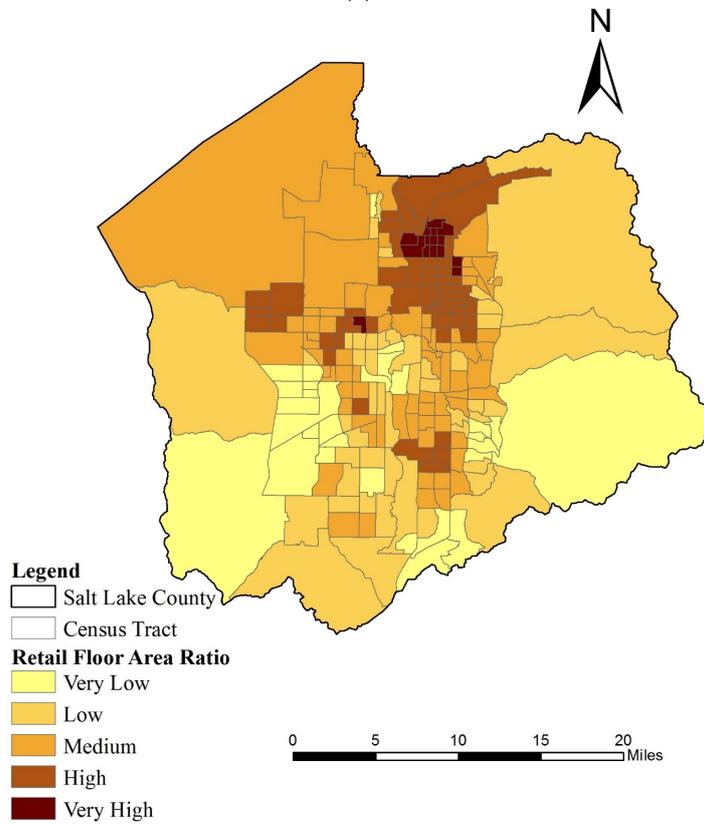
Figure 6 shows the spatial distribution of the dwelling density and retail floor area ratio. There are many similarities of the spatial distributions of these two variables in Salt Lake County. High dwelling density regions concentrate around the downtown and university areas while these regions also possess high retail floor area ratio.

In addition, the socio-demographic factors are significant in the OLS regression model. Age and education level are important determinants of walkability. Age has a positive effect on walkability, and the young families tend to walk less than comparatively older families. Education level is the most significant determinant in this model, as well-educated family walk more. This confirms the importance of education in promoting walkability [75].

To account for the spatial autocorrelation of PA in Salt Lake County, the spatial lag model is implemented and the results are presented in Table 3. Comparing these two models, the R^2 is improved from 0.45 to 0.46, which is not a significant improvement. However, the spatial lag variable is significant.



(a)



(b)

Figure 6. (a) Spatial distribution of dwelling density in Salt Lake County. (b) Spatial distribution of retail floor area ratio in Salt Lake County.

Table 3. Spatial lag regression result.

Variable	Coefficient	
	OLS Linear Regression Model	Regression Model with Spatial Lag
Accessibility		
<i>Distance to bus stop</i>	−0.037	−0.013
<i>Distance to light rail stop</i>	−0.061	−0.011
Amenity		
<i>Distance to park</i>	−0.152	−0.129
<i>Distance to worship</i>	0.232 *	0.221 *
Social economic status		
<i>Average AGE</i>	0.005 *	0.006 *
<i>Average education level</i>	0.735 ***	0.717 ***
<i>Vehicles per person</i>	−0.146	0.143
<i>Percentage of adult worker</i>	0.232	0.174
<i>Household income</i>	−0.037	−0.036
Land use		
<i>Dwelling density</i>	1381 *	1134 *
<i>Street connectivity</i>	−3196	−2346
<i>Land use mix</i>	−0.127	−0.093
<i>Retail floor area</i>	12.98 *	12.3 *
<i>Rho</i>	/	0.0022 *
Assessment		
R^2	0.4452	0.4593

Note: *** Significant at 0.01 level; ** Significant at 0.05 level; * Significant at 0.1 level.

6. Discussion

As we have discussed in the literature review, little work has been done to examine the impacts of geographical scales when testing the PA-walkability link. The 800-m road network buffer is usually considered to be the best choice to define the neighborhood [11,57]. However, the underlying reasons for the selection of this bandwidth is less discussed. This paper tests the performance of the four land use indicators, confirms the validity of the 800-m bandwidth, and finds the threshold for defining neighborhood (1600-m network buffer). On average, it is estimated that the 800-m walk takes 10 min and the 1600-m walk takes 20 min. However, 30-min moderate-vigorous PA on at least five days each week is recommended for adults [23,34] and 60 min for the youth [76]. Hence, most of the current neighborhood designs are unlikely to be sufficiently facilitate neighborhood residents to meet the PA recommendation.

This study employs the four-component walkability index as the land use indicators to explore people's walking minutes in Salt Lake County. With the 800-m network buffer defined as the neighborhood, the walkability index can explain about 15% variance of PA without any other control variables. The walkability index's contribution to the variance of PA is larger than what is reported in the research conducted in Atlanta and King County, Washington, wherein it respectively explains 10.7% and 8.3% variance of PA [11,12]. Hence, people's walking behavior relies on neighborhood land use more significantly in Salt Lake County. Since the neighborhood land use cannot meet the general requirement of at least 30 min moderate-vigorous PA, improving the density of the neighborhood land use will play an important role in promoting walkability in the future.

As the urban sprawl phenomenon is looming large in the United States, increasing population density and land use diversity is recommended to policy makers because the compact city with medium-high density housing can facilitate the sustainability of the city [77]. Numerous studies have

documented that increasing the density can decrease vehicle mile of travel (VMT) and create short trips [12,47,52]. The created short trips will make people walk more in the neighborhoods. In the northeastern area of Salt Lake County, the density is relatively high. But in other areas, the density is low. The government and policy makers should pay more attention to increasing the density in these areas.

Among the four traditional variables in walkability index, the land use mix is not significant at various geographical scales. One reason is that the relationship between land use mix and PA depends on the study area and trip type. After checking the destinations of the 490 trips taken by the 158 households, we find that over 200 trips are for exercising or walking with the dog. These trips are less likely to be affected by the mix-used land and are more likely to be influenced by neighborhood land use, personal preference and social demographic status. Another reason might be that Salt Lake County is at low mix land use level. The 2800 households covering the entire Salt Lake County are considered to calculate the four-category land use mix. The average value of land use mix in Salt Lake County is 0.22, while the land use mix values are 0.31 in King County and 0.38 in Atlanta [11,12]. Compared to these two well-developed regions, the mix use is relatively low in Salt Lake County.

Previous studies on the relationship between walkability and neighborhood environment rarely consider spatial autocorrelation. However, based on the result of Moran's I test, spatial autocorrelation should not be ignored. If we ignore the spatially lagged term, the coefficients in the regression model would be biased [78]. In this research, both OLS and spatial lag regression models are implemented and the regression results affirm that spatial lag regression model is a good method in this research. However, spatial lag regression model only considers the spatial autocorrelation in dependent variables (lagged dependent variable). Other spatial regression models should be employed in further studies.

7. Conclusions

As the obesity epidemic becomes a serious problem in the United States, physical inactivity, a risk factor of obesity, has drawn much attention. Promoting PA is good for sustainable development and people's health. Walking is a sustainable transport mode that is available to people without any impending costs, and can significantly increase the physical fitness of people. In recent years, several studies are being undertaken to examine the determinants of people's PA.

In this paper, PA is predicted by land use and walkability index, accessibility to transportation, and socio-demographic status. The walkability indices at various geographic scales are constructed and tested, suggesting that the spatial threshold for defining neighborhood for the purpose of examining PA is 1600 m. In addition, the dwelling density, street connectivity, and retail floor area ratio are significant determinants for PA while the land use mix is not. We also find that the best bandwidth for defining neighborhood is 800 m. An OLS linear regression model and a spatial lag model are employed to examine the relationship between neighborhood land-use, socio-demographic status, and PA. The results show that land use and socio-demographic status are the dominating determinants of PA. Density and compact design for land use are key elements in promoting PA and therefore efforts are still needed to improve density and compact design.

These findings should help researchers, policy makers and practitioners gain a better understanding of the determinants of PA so that effective interventions and programs can be implemented to achieve the sustainable development of cities. In a contrast to sprawling urban pattern, compact urban form and design can significantly improve neighborhood walkability and promote people's preference for walking. In future work, more urban evolution factors should be examined such as urban land expansion, which also influences PA and sustainability [79].

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