Royal Geographical Society with IBG
Advancing geography and geographical learning
AREA

Area, 2015, doi: 10.1111/area.12182

A GIS-based land-use diversity index model to measure the degree of suburban sprawl

Todd A Randall* and Brian W Baetz**

*Department of Geography and the Environment, Lakehead University, Thunder Bay, Ontario P7B 5E1, Canada
Email: randall@lakeheadu.ca

**Department of Civil Engineering, McMaster University, Hamilton, Ontario L8S 4L7, Canada

Revised manuscript received 2 January 2015

This paper describes a GIS-based land-use diversity measure for residential neighbourhoods – the land-use diversity index (or LDI) model – as a possible urban sustainability criterion. The term 'land-use diversity' is proposed as representative of many physical attributes of neighbourhood form opposite to typical sprawl patterns. A diverse neighbourhood is one with a mixture of compatible land uses and housing types, containing an array of amenities in reasonable proximity to where people live. The prototype version of the LDI model incorporates 34 input variables, structured around four sub-indices. Its range of expected values are explored through four case study applications. Theoretically, index values can vary between 0 and 1, where 1 represents a condition of greater 'land-use diversity'. The two traditional urban neighbourhoods fared well (index values ranging between 0.627 and 0.726) because they have a greater range of land uses and neighbourhood amenities, a better integration of housing types and are more concentrated. These two neighbourhoods meet many of the 'exuberant diversity' criteria described by Jacobs. The two suburban neighbourhoods scored lower index values (between 0.250 and 0.363), indicating variables different to those for traditional urban forms. The LDI model differs from existing sprawl measures fundamentally, as it attempts to measure sprawl at a finer resolution (i.e. at the neighbourhood scale). It is anticipated the LDI model will assist with planning new, and reconfiguring old, neighbourhoods as they strive to meet smart growth criteria now being considered by many cities.

Key words: *land-use diversity, traditional urbanism, suburban sprawl, Geographic Information System, sustainability indicator, sprawl index*

Introduction

Post-war suburban residential development (or sprawl) is widely criticised for a number of environmental and social problems that arise largely because of its physical layout. Alarmingly, these patterns have been replicated elsewhere including, but not limited to, Western Europe, which is often cited as having better models of urban form (Beatley 2000). Key physical problems of sprawl relate to its low density, segregation of land-use types and housing types, and the increasing distances from the traditional metropolitan core that such development form take (Ewing 1997; Benfield *et al*. 1999). Socio-economic consequences of sprawl include: the economic decline of central cities; the segregation of suburban residents along income lines; the rise of an auto-centric culture coincident with the loss of a pedestrian- and transit-centric culture; and the impact on health, and particularly obesity (Benfield *et al*. 1999; Speir and Stephenson 2002; Ewing *et al*. 2003; Frank *et al*. 2005). In essence, conventional suburban development has been plagued by a lack of diversity and vibrancy, as described by Jacobs (1961).

With hopes of negating or abating suburban sprawl there is an ever-growing body of literature outlining what constitutes 'good urban form' or 'smart growth' (Clifton *et al*. 2008), building on the concept of 'exuberant diversity' described by Jacobs (1961). Good urban form largely replicates the pattern of traditional urbanism commonplace in North American cities in the early 20th century, largely built on streetcar and pre-car templates (Katz 1994). These require a mixture of primary uses and a sufficiently high concentration of people and activities

(Jacobs 1961). Traditional urbanism employs mixed land use, modestly-higher densities, and supports economically viable public transit services. Talen wrote that the smart growth planning movement is 'focussed on providing urban development that is compact, diverse and walkable as opposed to car-dependent and land-consumptive' (2003, 195). Proponents of smart growth and neo-traditional design models of development purport that these characteristics will lead to residential development that is more sustainable than the conventional suburban model. It is argued the former models are more sustainable because they use less material and land resources to construct and maintain (Talen 2003), are less reliant on the automobile (Calthorpe 1993), lead to an improved social harmony at the neighbourhood level (Duany *et al*. 2000), and offer financial advantages over the conventional suburban pattern (Munro 2004).

Based on literature relating to good urban form, smart growth, the measurement of 'land-use diversity' in this study, incorporates the following four broad characteristics:

- the diversity of land-use types and the degree to which they are mixed
- the diversity of housing types and the degree to which they are mixed, implying a mixed socio-economic population as well
- the range of goods and services present within the neighbourhood
- the proximity of a neighbourhood's residents to some key (commonly sought) neighbourhood amenities or services.

The overall aim of this study was to develop a GIS-based index model, herein referred to as the land-use diversity index (LDI) model, to quantify the concept of land-use diversity for a residential neighbourhood. More diverse, less homogeneous neighbourhoods are considered more environmentally and socially sustainable, but Talen (2003) pointed to a need for new measurement tools to evaluate emerging urban forms like neo-traditional design and smart growth, otherwise these concepts will prove intangible. The LDI model contributes to the literature measuring neighbourhood design patterns, including suburban sprawl and walkability of urban areas (Frank *et al*. 2005), and could be used to create a measure of more sustainable urban form. The LDI model differs from other sprawl measures in two key ways. First, it is a measure developed at the scale of a neighbourhood, unlike others using aggregated statistics over a much coarser scale (e.g. entire city or metropolitan area [Ewing *et al*. 2002; Frenkel and Ashkenazi 2008; Schwarz 2010]). Knaap *et al*. (2007) suggested that there is greater utility in urban form measures at finer resolutions. Second, the LDI model aims to create an 'absolute' measure of land-use diversity rather than a 'relative' measure of sprawl. In a relative modelling approach, one study area would be contrasted against another, with the conclusion that one was less or more sprawl-like. In an absolute modelling approach, the results from a study area would be compared to the theoretical preferred condition of land-use diversity.

In addition to its contribution to the academic discussion of sprawl and land-use diversity metrics, the LDI model is targeted towards professional practitioners who are wrestling with questions about how to meet targets for the intensification and diversification of residential areas. For example, in the Places to Grow legislation (Province of Ontario 2006), Ontario municipalities have specific targets with respect to residential intensification and other principles of smart growth and urban sustainability. Given the implied use for planners, the LDI model has been conceptualised with standard digital data typically available for a given municipal jurisdiction. The approach is broad enough that the LDI model framework is portable to other Canadian, American and potentially international contexts.

The paper begins with a description of the LDI model. This is followed by its application to several residential neighbourhoods in order to explore the range of index values for a spectrum of traditional urban and conventional suburban neighbourhoods, which represent an initial calibration of the LDI model.

Conceptual model: methods and data requirements

The LDI model was developed around four broad characteristics of land-use diversity. These characteristics all reflect more diverse and more sustainable urban forms and support several principles of smart growth (Table 1). For each characteristic, a distinct sub-index model was constructed so that the overall LDI model is composed of four sub-indices. This section provides an overview of each sub-index, including: its specific objectives; its context within the overall LDI model; the input variables, including any GIS operations necessary to derive these values; model parameters such as variable weightings and target values; and the anticipated physical meaning of the results.

Mix of housing types

This sub-index quantifies the variety of housing types included and mixed within a residential neighbourhood. While urban and suburban neighbourhoods contain both single family and multi-family dwellings, it is the relative mixtures that differentiates the two neighbourhood forms as well as the intensity at which these neighbourhoods are

Area 2015 doi: 10.1111/area.12182

Table 1 Characteristics of residential development considered in the land-use diversity index (LDI) model in comparison to the principles of smart growth

LDI model sub-index	Characteristic of residential development (this study)	Corresponding Principle of Smart Growth (see Smart Growth BC 2014)
1	The **diversity of land uses** and the degree to which they are **mixed**	**(Principle 1) Mix land uses**. Each neighbourhood has a mixture of homes, retail, business and recreational opportunities
2	The **diversity of housing** types and the degree to which they are **mixed**, implying a mixed socio-economic population as well	**(Principle 4)** Create **diverse housing opportunities**. People in different family types, life stages and income levels can afford a home in the neighbourhood of their choice
3	The **range of goods and services** that are present within the neighbourhood	None
4	The **proximity** of a neighbourhood's residents to some key fundamental **neighbourhood amenities or services**	**(Principle 2)** Build well-designed compact neighbourhoods. Residents can choose to **live, work, shop and play in close proximity**. People can easily access daily activities, transit is viable and local businesses are supported

Notes: There are 10 principles listed at Smart Growth British Columbia (2014). Those that are addressed by the LDI model are summarised in the right-hand column with significant text passages in bold

built. In a typical suburban neighbourhood, higher density (i.e. multi-family) housing types are often concentrated (or clustered) at the neighbourhood's perimeter along busy arterial roads, while the central portions of the neighbourhood are reserved for lower-density, single family dwellings. Therefore, neighbourhoods characteristic of traditional urbanism are usually of moderate residential densities and have greater representation and mixing of dwelling types in comparison to sprawl neighbourhoods (i.e. those having low density and greater housing segregation). This sub-index contains eight variables (Table 2). The housing type variables are normalised to their neighbourhood populations to facilitate comparisons and the 'sprawl condition' indicates what magnitude of values suggests a more sprawl-like neighbourhood.

Clustering of housing types is quantified using the Nearest Neighbour Statistic (NNS), a spatial statistic tool found in ESRI's ArcGIS. An NNS calculates an index value based on the average distance from each polygon feature's centroid (in this case, an individual residential building) to its nearest neighbouring centroids. The average value of all of these nearest neighbour distances is compared with a hypothetical random distribution of centroids; this ratio is the Local Moran's I value (i.e. equivalent to the NNS) (ESRI 2009). The critical value for interpretation is '1'. Values of 1 suggest the pattern of centroids is 'random' (i.e. neither clustered or dispersed); values less than 1 are 'clustered'; and values larger than 1 are 'dispersed'. On the clustered end of the spectrum, values closer to 0 demonstrate a stronger degree of spatial clustering. Some of the anticipated clustering variable behaviour is observed by way of an example (Figure 1), namely that multi-family housing types demonstrate a stronger clustering pattern than single family homes in residential neighbourhoods.

The final variable in this sub-index is gross residential density. Although one of the simplest density calculations in a GIS, it is also a key variable when comparing one neighbourhood form against another (e.g. Southworth 1997; Gordon and Vipond 2005; Millward and Bunting 2008). It is also an appropriate metric to use when citing the net residential densities used as transit viability thresholds (Pushkarev and Zupan 1982). Gross residential density represents the same number of transit customers per neighbourhood as if the density had been calculated as a net residential density.

For each sub-index of the LDI model, the input variables are combined using a weighted linear combination approach to create a sub-index value between 0 and 1. Values tending towards 1 represent a condition of greater land-use diversity (the desired condition with respect to urban sustainability criteria), and values tending towards 0 are more sprawl-like (the least desired condition). Each input variable has a range of values, based either on observations of several neighbourhoods or on expected values derived from the literature, and is standardised using the appropriate form of equation (1). The S_i values should be between 0 and 1 and are checked to ensure they generate appropriate values. For example, low values for residential density should result in low standardised values (approaching 0) as low residential densities correspond with a condition of suburban sprawl.

Table 2 Input variable descriptions, sprawl conditions and weightings for the land-use diversity index (LDI) sub-index 1: mix of housing types

Variable ID	Description	Units	Sprawl condition	Weighting factor
pc_sfh	# of households in single family homes per 1000 population[a,b]	du/1000	Higher values; postwar sprawl neighbourhoods are primarily bedroom communities of detached single-family dwellings;	10%
pc_dupl	# of households in duplexes per 1000 population[b]	du/1000	Lower values; sprawl neighbourhoods are less mixed than traditional urban neighbourhoods	10%
pc_rowh	# of households in rowhouses per 1000 population[a,b]	du/1000		10%
pc_apt	# of households in apartments per 1000 population[a,b]	du/1000		10%
cl_dupl	Clustering of duplexes[c]	–	Lower values; values less than 1 indicate clustering, hence values tending towards zero are *more* clustered; clustering of dwelling types is characteristic of sprawl because dwelling types are typically segregated from one another	10%
cl_rowh	Clustering of rowhouses[c]	–		10%
cl_apt	Clustering of apartments[c]	–		10%
gr_dens	Gross residential density (dwelling units/hectare)	du/ha	Lower values; sprawl neighbourhoods typically have lower residential density than traditional urban neighbourhoods	30%

[a] Single-family homes in this table include detached homes, estate-detached homes and mobile homes, if applicable. Rowhouses include dwellings classified using the interchangeable names of ‘rowhousing’ or ‘townhouses’. Apartment homes include apartment dwellings, cooperative housing units, dormitory housing and lodging/boarding/rooming housing. [b] The housing type tallies have been normalised using the neighbourhood population (tallies are divided by the neighbourhood population then multiplied by 1000). [c] The clustering variables were derived from a Nearest Neighbour statistic in ArcGIS and can only be interpreted if and only if the Z-score is significant; for significance to the 95% confidence level, the Z-score must be >+2.00 or <–2.00

$$S_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \quad \text{or} \quad S_i = 1 - \left[\frac{X_i - X_{\min}}{X_{\max} - X_{\min}}\right] \tag{1}$$

where S_i = standardised value for variable i; X = original values for variable i.

Each variable has a ‘weighting factor’ used to designate its relative importance in the overall index model (see equation 2). As the LDI model is a new conceptualisation, there is not a definitive list of variable weights available. For most of the variables, equal variable weights were applied, except in cases when a variable was deemed to be more important, based on the literature (e.g. weighting of gross residential density at 30% of sub-index 1; Table 2).

$$I = \frac{\sum_{i=1}^{n} w_i S_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

where I = index value; n = the number of variables; w_i = weight for variable i; S_i = standardised value for variable i.

Mix of land-use types

This sub-index quantifies the degree to which land-use types are mixed in a residential neighbourhood (Table 3). Both urban and suburban residential neighbourhoods are commonly dominated by their residential land-use component. Traditional urban neighbourhoods tend to be more diverse and can have higher percentages of non-residential land uses, particularly commercial and (compatible) light industrial uses. Both neighbourhood forms tend to have similar allocations for institutional and roadway land uses, though differences can emerge when per capita allocations are considered. Hofmann (2006) demonstrated that a neo-traditional design layout has a lower per capita road area allocation than the same area built as a conventional suburban neighbourhood. Hence, for comparison purposes, all land-use variables are normalised to their respective neighbourhood populations. Expected values suggesting sprawl are high (per capita) for residential and green space land uses and low (per capita) for commercial, institutional and industrial land uses (Table 3). A second key difference expected is the spatial distribution of the various land uses. Analogous to the mix

Area 2015 doi: 10.1111/area.12182

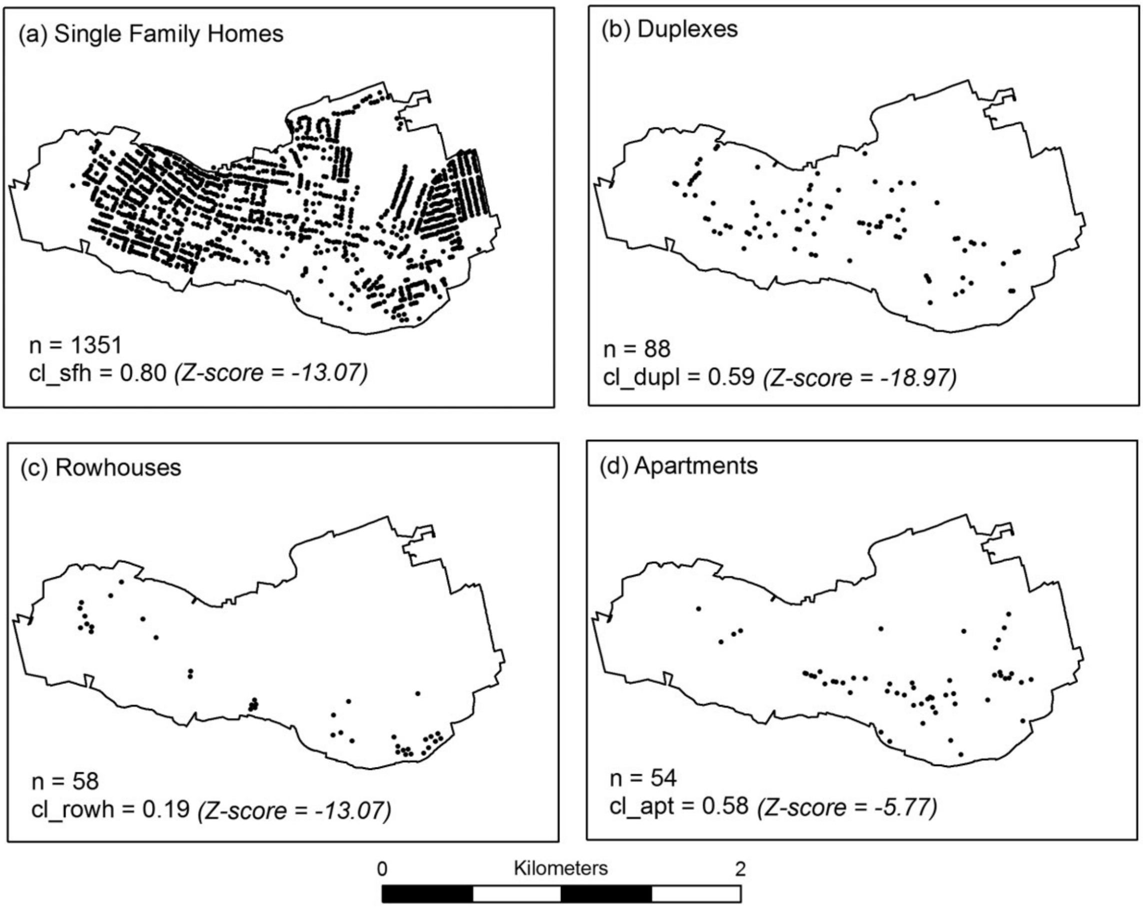

Figure 1 Clustering for housing types variables for the Dundas study neighbourhood based on the Nearest Neighbour Statistic (NNS)

Note: In each map, one dot represents one centroid of a given residential building. Patterns that are more strongly clustered are less than 1 and closer to 0

of housing types, there is an expectation that land uses in a traditional urban residential neighbourhood are more spatially mixed (dispersed), while those in a suburban residential neighbourhood are more segregated (clustered). The spatial distribution of residential and commercial land uses have been quantified using the NNS described earlier.

Amenities mix

This sub-index quantifies the range of goods and services (i.e. amenities) present within a residential neighbourhood. These include those categorised as 'daily amenities', like an elementary school, a convenience store or a grocery store, as well as a range of amenities one uses less frequently but are still convenient to have within or close to a neighbourhood (e.g. pub, church, library, bank, doctor). The number and diversity of such amenities depend largely on the time period during which the neighbourhood was constructed. Traditional urban neighbourhoods of the early 20th century were centred on linear shopping districts (located along streetcar lines) and these surviving districts contain a diverse array of amenities available to adjacent residential neighbourhoods. The communities of 'small town Ontario' or 'Main Street USA' fit this concept. At the other end of the spectrum are conventional suburban neighbourhoods that either lack non-residential amenities or have only a limited number.

This sub-index contains ten variables relating to the range of amenities deemed compatible with a residential neighbourhood (Table 4). A functioning 'Main Street' was selected as the desired style of retail development meeting the broad desires of a more sustainable neighbourhood (i.e. greater abundance and variety of amenities). The

Table 3 Input variable descriptions, sprawl conditions and weightings for the land-use diversity index (LDI) sub-index 2: mix of land-use types

Variable ID	Description	Units	Sprawl condition	Weighting factor
pc_area_res	Per capita residential land (ha per 1000 population)[a]	ha/1000	Higher values; lot sizes are larger, and more detached dwellings with bigger yards are present in suburban neighbourhoods	10%
pc_area_comm	Per capita commercial land (ha per 1000 population)[a]	ha/1000	Lower values; there are fewer non-residential activities in a suburban versus urban residential neighbourhood	10%
pc_area_inst	Per capita institutional land (ha per 1000 population)[a]	ha/1000		10%
pc_area_ind	Per capita industrial land (ha per 1000 population)[a]	ha/1000		10%
pc_area_grsp	Per capita green space (ha per 1000 population)[a]	ha/1000	Higher values; suburban neighbourhoods on the periphery of cities would have a greater area of public green spaces like parks, riverine corridors, etc.	10%
pc_area_roads	Per capita road area (ha per 1000 population)[a]	ha/1000	Higher values; infrastructure investments like roads and sewers are higher per capita in suburban neighbourhoods (supported by Munro 2004); the model by Hofmann (2006) showed that neo-traditional design has a lower per capita road area than same neighbourhood built as conventional suburban development	10%
cl_res_pcls	Clustering of residential area parcels[b,c]	–	Lower values; values less than 1 indicate clustering, hence values tending towards zero are *more* clustered; clustering of land uses is characteristic of sprawl because land uses are typically segregated from one another in the design of such neighbourhoods	15%
cl_comm_pcls	Clustering of commercial area parcels[b,c]	–		15%

[a] Land-use area values have been normalised using the neighbourhood population (land-use areas are divided by the neighbourhood population then multiplied by 1000). [b] The clustering variables were derived from a Nearest Neighbour statistic in ArcGIS and can only be interpreted only if the Z-score is significant. For significance at the 95% confidence level, the Z-score must be >+2.00 or <–2.00. [c] Cluster variables for all land-use types was initially considered but because residential neighbourhoods have few land-use parcels for institutional, industrial and green space uses these other variables were discarded because of insignificant Z-scores in nearly all neighbourhoods considered

commercial centre of the small town of Dundas (Ontario) was selected as a *functioning* main street, because it has a mixed-use, old town centre in which real-life daily needs are met. All commercial and institutional enterprises recorded there (totalling 275) were assigned a code according to the North American Industry Classification System (or NAICS) (Statistics Canada 2007b). Other functions listed with the NAICS and deemed compatible with residential neighbourhoods were also included in the sub-index variables. The variable values are the total number of enterprises or businesses in a given category that are normalised to the neighbourhood population. As with the other sub-indices, there is limited literature regarding variable weightings. Four of the ten variables were weighted slightly more strongly based on previous research (see note 2; Table 4).

Access to amenities

This sub-index quantifies the accessibility (i.e. walkability) to some commonly used neighbourhood amenities, namely supermarkets, convenience stores, bus stops and elementary schools (Table 5). If such amenities are within a reasonable distance of where people live, then a resident may choose to walk to that amenity rather than to drive (Barton *et al.* 2003). A design distance of 400 m is often used as a 'reasonable' walking distance in generating pedestrian catchments (Atash 1994; Hess 1997). The above key amenities were selected for two main reasons: one, they are key amenities identified by respondents in a neighbourhood preferences survey (Randall 2008); and two, all four are common in (or located near to) most residential neighbourhoods (urban or suburban) and therefore thought to represent fair

Table 4 Input variable descriptions, sprawl conditions and weightings for sub-index 3 (Amenities Mix)

Variable ID[a]	Service category[2]	Types of amenities included in the service category[c]	Units	Sprawl condition	Weighting factor
pc_pers_gs	Personal goods and services	Relates to personal items (e.g. clothes, grooming), items for personal consumption (e.g. books, DVD rental, florist, postage) and personal finance (banking, insurance, wealth management)	#/1000	lower values; sprawl typically lacks neighbourhood amenities or has a very small number of these;	15%
pc_house_gs	Household goods and services	Relates to items for the construction of and maintenance of home and automobiles (furniture, building and gardening supplies, car dealerships, service stations, contractors and other trades)	#/1000	a functioning main street retail, like that found in Dundas, Ontario – by contrast – has a	7.5%
pc_health_gs	Healthcare goods and services	Relates to the physical and mental health care needs of individuals and families, including daycare, dental, doctor and other health care professionals, as well as nursing and residential car facilities.	#/1000	considerable number of amenities in these goods and services	15%
pc_proftech	Professional and technical services	Includes real estate, legal, accounting, engineering, consulting and other professional services	#/1000	categories;	7.5%
pc_govt	Government services	Includes police/fire protection services, and municipal and provincial government offices	#/1000		7.5%
pc_inst	Institutional facilities	Includes libraries, elementary and secondary schools, hospitals, universities and colleges, and religious organisations	#/1000		15%
pc_tourrec	Tourism, entertainment and recreation	Includes travel agencies, museums, hotels/motels, fitness centres, community centres and other tourist and recreational services	#/1000		7.5%
pc_food_sales	Food and beverage retail	Includes supermarkets, convenience stores, beer and liquor stores	#/1000		15%
pc_food_serv	Food services	Includes restaurants, bars, pubs	#/1000		7.5%
pc_transpo_gs	Transportation goods and services	Includes taxi services, auto maintenance and repair, auto rental and parking lots	#/1000		7.5%

Notes: Variable service categories were developed in consultation with the North American Industry Classification System (Statistics Canada 2007b) to include services and amenities thought potentially compatible to a residential neighbourhood. [a] Each of these goods and services categories is standardised to the neighbourhood population. Variable units are the number of amenities present per 1000 population. [b]The four predominant categories of amenities are Personal Goods and Services, Healthcare Goods and Services, Institutional Facilities, and Food and Beverage Retail (highlighted in grey) based on the typical preferences in a residential neighbourhood for personal amenities, healthcare providers, a nearby elementary school, supermarket and convenience stores (see Randall 2008). Each of these has been more strongly weighted (15%) in the sub-index. [c] The list of amenities present in these variable category descriptions is not exhaustive. A complete listing of amenities and NAICS codes used in the sub-index is available from the authors.

assessment criteria. All input variables were determined with ArcGIS's Network Analysis 'closest facility' operation. With respect to the LDI model, the desired conditions are lower route distances to and a higher fraction of residents within walking distance (<400 m) of a given amenity. It is anticipated that residents in an urban residential neighbourhood are in closer proximity to amenities because of efficiencies gained via a grid street pattern (versus curvilinear ones) and the greater concentration of customers afforded by higher densities.

Table 5 Input variable descriptions, sprawl conditions and weightings for the land-use diversity index (LDI) sub-index 4: Access to amenities

Variable ID	Description	Units	Sprawl condition	Weighting factor
rtedis_supmkt	Proximity to supermarkets (average route distance from each dwelling unit to nearest supermarket)[a]	m	Higher values; urban residential forms are more compact and more diverse than suburban forms and there are a greater number of amenities present in the former; thus, it stands to reason that supermarkets, convenience stores, bus stops and (potentially) elementary schools would be further away from a higher percentage of a suburban neighbourhood's residences (higher route distances)[b]	12.5
rtedis_conv	Proximity to convenience stores (average route distance from each dwelling unit to nearest convenience store)	m		12.5
rtedis_busstop	Proximity to transit (average route distance from each dwelling unit to nearest bus stop)	m		12.5
rtedis_elemsch	Proximity to elementary schools (average route distance from each dwelling unit to nearest elementary school)	m		12.5
pc_supmkt	% of dwelling units within 400 m of supermarkets	%	Lower values; for a similar rationale as the route distance variables, a suburban residential neighbourhood will have lower percentages of its dwellings within walking distance (i.e. within 400 m) of these amenities because suburban neighbourhoods have lower residential densities and street patterns that lengthen route distances (Randall and Baetz 2001)	12.5
pc_conv	% of dwelling units within 400 m of convenience stores	%		12.5
pc_busstop	% of dwelling units within 400 m of bus stops	%		12.5
pc_elemsch	% of dwelling units within 400 m of elementary schools	%		12.5

Note: Proximity variables (rte_dis_supmkt, etc) were developed to assess the walkability of a neighbourhood (i.e. whether or not the distances to the listed amenities were within a walking distance of 400 m). [a] A 'supermarket' was determined to be the point locations of a major grocery chain retailer having a large commercial floor area like Safeway, Atlantic & Pacific (A&P), Great Canadian Superstore, The Barn, Food Basics, but does not include smaller neighbourhood independent 'grocery' stores. [b] The route distance to schools might not agree with this overall trend because suburban neighbourhoods were often built with a focal point on the neighbourhood elementary school, and urban neighbourhoods having older populations may have experienced a number of inner-city school closures. Hence schools may appear less accessible by walking in older, inner-city neighbourhoods than in newer sprawl areas. However, in theory, schools should be more accessible in urban neighbourhoods because of their overall intensity and the favourable street configuration.

Model summary

The four sub-indices of the LDI model capture a range of the physical attributes of residential neighbourhoods. Neighbourhoods are considered more diverse if they have most of the following characteristics:

- a mix of housing types and are of moderate density
- a mix of compatible land-use types
- a range of amenities compatible with residential development and
- some of the typical daily amenities within walking distance of where people live.

Each of these characteristics is the central idea behind the LDI's sub-indices. Like each sub-index, the overall LDI model is calculated using a weighted linear combination approach, generating values between 0 and 1, where values that tend towards 1 represent a condition of greater land-use diversity (i.e. desired sustainability condition).

Results and discussion

Four applications of the LDI model to suburban and traditional urbanism neighbourhoods serve as a preliminary model calibration. The authors acknowledge neighbourhoods exist whose values for some variables and sub-indices will be outside the ranges presented here. The case study neighbourhoods were selected from two Census Metropolitan Areas (CMA) (Figure 2). The choice of neighbourhoods from two CMAs was due to related research comparing the responses of residents in the two cities to residential intensification strategies (i.e. Randall 2008), but there was no intention to compare results (city versus city) for the LDI model at that time. Hamilton CMA

Area 2015 doi: 10.1111/area.12182

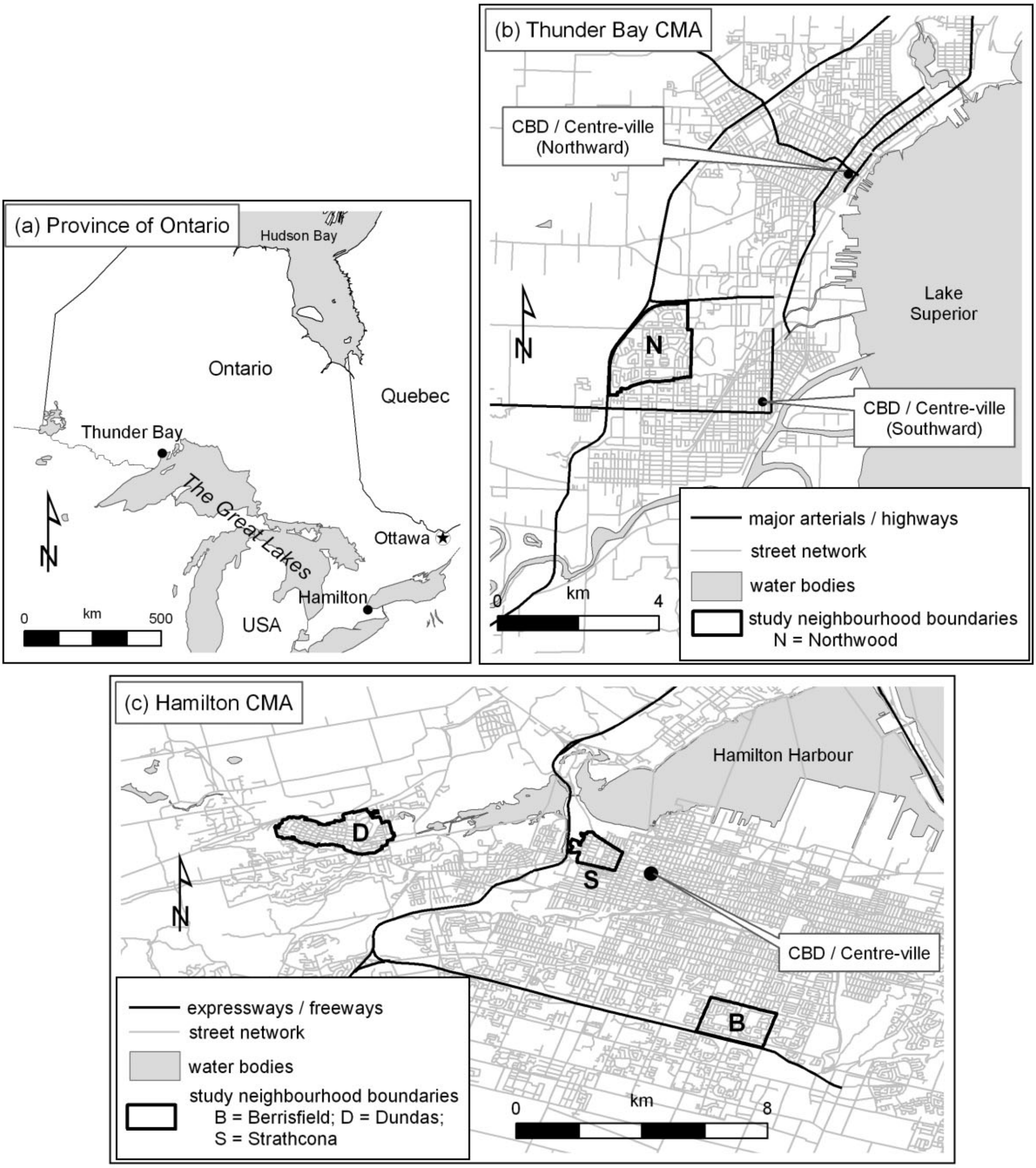

Figure 2 (a) Locations of Hamilton and Thunder Bay, Ontario; (b) Northwood study neighbourhood in the Thunder Bay CMA in relation to its central business districts (CBDs); and (c) Berrisfield, Dundas and Strathcona study neighbourhoods in the Hamilton CMA

Note: CMA = Census Metropolitan Area, a term used for Canadian metropolitan agglomerations larger than 100 000 (Statistics Canada 2007a)

Area 2015 doi: 10.1111/area.12182

is a medium-sized city located in southern Ontario with a metropolitan population of approximately 690 000 (Statistics Canada 2007a). Thunder Bay CMA is a smaller city located in northwestern Ontario with a metropolitan population of approximately 123 000 (Statistics Canada 2007a). Neighbourhoods were chosen by considering their characteristics and by consulting with local planners. The two suburban neighbourhoods (one for each CMA) were constructed primarily during the 1960s and 1970s and had a range of housing types. It was also important neighbourhoods had basic amenities like a nearby supermarket and an elementary school. Each suburban neighbourhood is dominated by its residential and road allocations, with only a small representation of commercial and institutional land uses (Table 6). The two urban neighbourhoods date from the late 19th to early 20th century. Hamilton's Strathcona neighbourhood has been subject to considerable study, given that it is an inner city neighbourhood close to the CBD. The other is the old central core of the small town of Dundas, amalgamated into the larger new City of Hamilton in 2000. Despite its 'peripheral' location (Figure 2c), the central core of Dundas is one of the best examples of a *functioning* 'Main Street'. It was anticipated Dundas might represent a desirable condition of urbanism, one with only modest residential densities but with a significant presence of *compatible* non-residential land uses and amenities (Table 6).

Mix of housing types

Not surprisingly, the two suburban neighbourhoods are dominated by high percentages of single family homes, though both contain notable percentages of multi-family housing types (Table 7). The higher percentages of rowhouses and apartments in Berrisfield, however, result in it having an overall higher gross residential density than Northwood (Table 6). The two urban neighbourhoods display results both expected and unexpected. Dundas has an expected lower fraction of single family homes and a larger fraction of apartments (Table 7). These apartments are primarily low-rise apartment buildings or apartment units found above ground-level commercial enterprises. In Strathcona, the fraction of apartment dwellings exceeds the single family home fraction (due to similar factors as those for Dundas) as well as the presence of several modest-scaled high-rise apartments.

The housing-mix sub-index is lowest for the two suburban neighbourhoods (0.276 to 0.355; Table 8) due to their having more single family homes and fewer multi-family housing types (on a per capita basis). In addition, the spatial distribution of multi-family housing types is also more strongly clustered for these neighbourhoods. Patterns observed in Berrisfield typify suburban sprawl, with concentrations of multi-family dwellings along busy arterial roads at the neighbourhood periphery (Figures 3b and 3c) or as 'clusters' within a more central portion of the neighbourhood (Figure 3a). The opposite condition is true

Table 6 Land-use composition of the study neighbourhoods used in the development of the land-use diversity index (LDI) model

	Neighbourhood name			
	Northwood	Berrisfield	Dundas	Strathcona
Neighbourhood type	Suburban	Suburban	Urban	Urban
Total neighbourhood area	326.9 ha	184.9 ha	233.7 ha	88.4 ha
Residential land area	51.5%	55.8%	46.2%	41.0%
Commercial land area	1.8%	2.3%	8.6%	9.6%
Institutional land area	6.5%	6.9%	5.1%	13.3%
Industrial land area	0.0%	0.1%	8.5%	0.0%
Green space land area	14.7%	5.1%	12.4%	10.0%
Area of roads	25.4%	29.9%	23.4%	28.8%
Sum (land-use percentages)[a]	100.0%	100.0%	104.1%	102.7%
Gross residential density (LDI model)[b]	11.2 du/ha	14.4 du/ha	11.9 du/ha	22.9 du/ha
Gross residential density (Census)[c]	10.6 du/ha	13.9 du/ha	12.6 du/ha	33.9 du/ha
Net residential density (LDI model)	21.7 du/net res. ha	25.9 du/net res. ha	25.7 du/net res. ha	55.9 du/net res. ha

[a] The sum of land-use percentages does not necessarily add up to 100.0% as parcels in older urban neighbourhoods can be zoned for multiple uses, that is they have a primary land-use code (PLUC) and a secondary land-use code (SLUC). This is especially true of multi-story buildings along arterial streets that have ground-level retail (zoned commercial) with apartment units on the upper stories (zoned residential). [b] Density values based on the calculations in the LDI model. [c] Gross residential density based on data for dissemination areas from the 2001 Census (Statistics Canada 2002)

Source: Results derived from parcel databases from the City of Thunder Bay (for Northwood) and the City of Hamilton (for Berrisfield, Dundas and Strathcona)

Area 2015 doi: 10.1111/area.12182

Table 7 Dwelling-unit composition of the study neighbourhoods used in the development of the land-use diversity index (LDI)

	Neighbourhood name			
	Northwood	Berrisfield	Dundas	Strathcona
Neighbourhood type	Suburban	Suburban	Urban	Urban
Total # of dwelling units	3646 du	2666 du	2774 du	2025 du
% single family	68.2%	62.3%	48.7%	39.8%
% duplex	17.3%	8.0%	6.3%	10.6%
% rowhouse	3.3%	14.3%	9.8%	4.5%
% apartment	11.2%	15.5%	35.1%	45.1%
Gross residential density (LDI model)	11.2 du/ha	14.4 du/ha	11.9 du/ha	22.9 du/ha

Source: Field verification by the researchers of residential zoning codes that were indicated on zoning maps obtained from the cities of Thunder Bay (for Northwood) and Hamilton (for Berrisfield, Dundas and Strathcona)

Table 8 Values obtained for the land-use diversity index (LDI) for the study neighbourhoods considered in this study

	Northwood (sub)	Berrisfield (sub)	Dundas (urb)	Strathcona (urb)
Sub-index 1 = (mix of housing types)	0.276	0.355	0.408	0.731
Sub-index 2 = (mix of land-use types)	0.196	0.388	0.499	0.699
Sub-index 3 = (mix of amenities)	0.112	0.155	0.983	0.696
Sub-index 4 = (access to amenities)	0.416	0.553	0.619	0.778
LDI =	0.250	0.363	0.627	0.726

Notes: The four study neighbourhoods are classified as either urban (urb) or suburban (sub). The four sub-indices are equally weighted at 25% each in the computation of the combined LDI. The LDI value can take values on the range of 0 to 1 where 1 indicates a condition of greater 'land-use diversity'. Values that approach one (1) are more diverse while those that approach zero (0) are more 'sprawl-like'

of the urban neighbourhoods, with greater dispersal of multi-family housing types, particularly for duplexes and apartments (Figure 3). And finally, lower values of the residential density variable are obtained for the two suburban neighbourhoods (as expected), but also for urban Dundas (not expected). The low-density figure for Dundas is partially explained by its larger complement of non-residential land-use functions (Table 6).

Mix of land-use types

The tabulated land-use areas for the four neighbourhoods demonstrate an expected pattern. Most of the suburban neighbourhoods are devoted to residential, road and green space uses, with only small components of commercial and institutional uses (Table 6). The urban neighbourhoods, by contrast, are more diverse with respect to land use, while maintaining or increasing overall density. Significant fractions of commercial, institutional and even industrial land uses are present (Table 6). Dundas' industrial component is unique because of it being a former town core, yet represents a functioning example of compatible industrial land use in relatively close proximity to a residential neighbourhood (Figure 4).

Values of this sub-index are lower for the two suburban neighbourhoods (0.196 to 0.388; Table 8), as might be expected, because they have higher per capita components of residential area, green space and roads, and lower per capita components of commercial and industrial areas. The suburban neighbourhoods returned a more dispersed pattern for clustering of residential parcels, counter to that expected, because there are fewer non-residential land-use parcels to segregate the residential ones, thereby increasing the NNS results. Sub-index values for the two urban neighbourhoods (0.408 to 0.731; Table 8) are more consistent with the expected values for Strathcona than they are for Dundas. Strathcona demonstrates the desired condition for greater land-use diversity with a significant per capita commercial component and with lower per capita areas devoted to residential, green space and roads, corroborating the point made earlier that traditional urban neighbourhood designs have lower per capita road allocations (Hofmann 2006) and, hence, lower per capita infrastructure and maintenance costs (Munro 2004). Dundas was weakened by its having the lowest per capita institutional area, probably due to the suburbanisation of many of its schools.

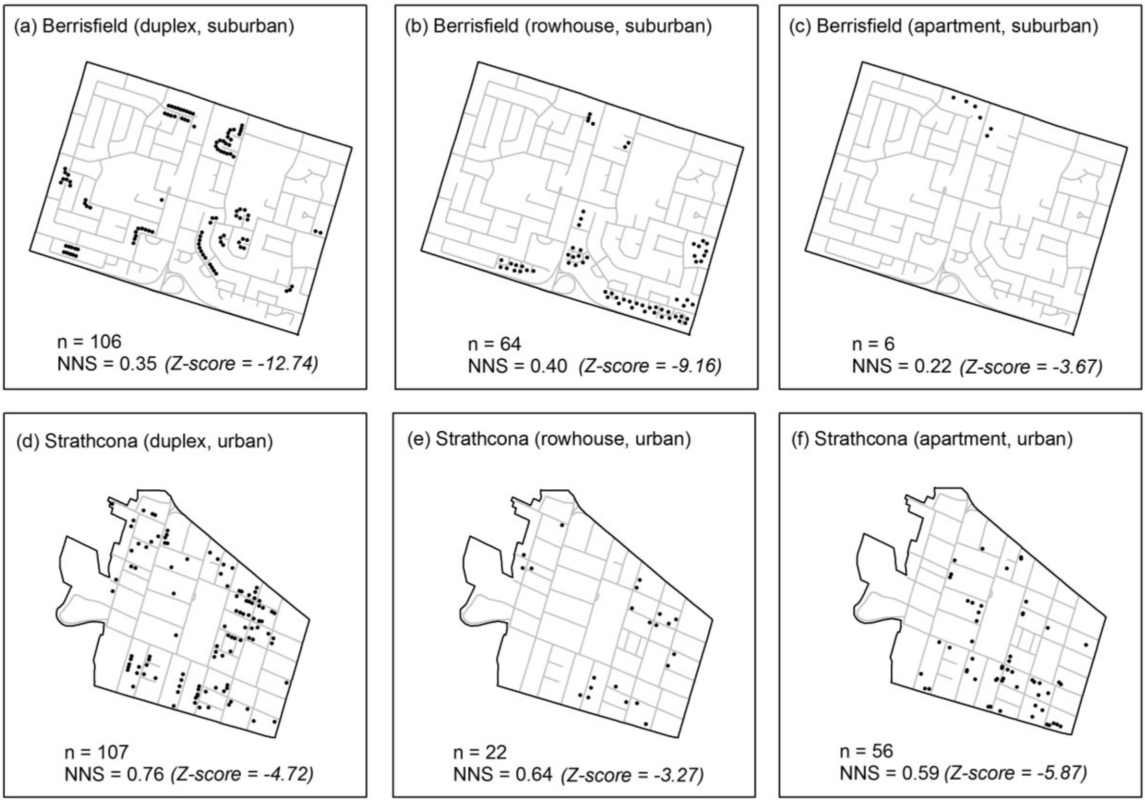

Figure 3 Spatial distribution of multi-family dwelling types and the related values of variables measuring their degree of clustering

Note: The suburban neighbourhood example (Berrisfield, top 3 boxes) shows a stronger degree of clustering for each of the dwelling types than the more dispersed patterns observed in the traditional urban neighbourhood example (Strathcona, bottom 3 boxes)

Amenities mix

The amenities-mix sub-index values are lower for the two suburban neighbourhoods (0.112 to 0.155; Table 8). This is not surprising because both urban neighbourhoods have a much higher commercial land-use fraction (Table 6), meaning there were many more locations in which to develop commercial enterprises. Moreover, in a neighbourhood like Strathcona, its residential density is also substantially higher than the suburban neighbourhoods, providing a larger number of potential customers to support local commercial development. The results in Table 8 support the assertion that Dundas contains a considerable breadth of amenities and could be considered as some sort of ‘target condition’. However, having four study neighbourhoods is not sufficient to adequately capture the range of possible neighbourhoods, so Dundas remains a good example of urbanism if not the definitive or desired end condition. Strathcona does demonstrate a considerable range of amenities and could serve as a more realistic target condition given its performance in the other sub-indices and the overall LDI model.

Access to amenities

The results of this sub-index provide a measure of the overall walkability of a neighbourhood with respect to each of the amenities considered and suggest the following: bus stops are readily accessible for all neighbourhoods considered; convenience stores are within walking thresholds for the urban but not the suburban neighbourhoods; schools are accessible by walking only for Strathcona; and a supermarket is not really a ‘neighbourhood’ amenity because the average route distances all exceed 400 m. When considered as a ‘fraction having pedestrian access’ to an amenity, some differences begin to appear. For example, urban neighbourhoods afford good access to convenience stores in contrast to the suburban neighbourhoods (Figure 5), in large part due to the convoluted street network patterns (Southworth and

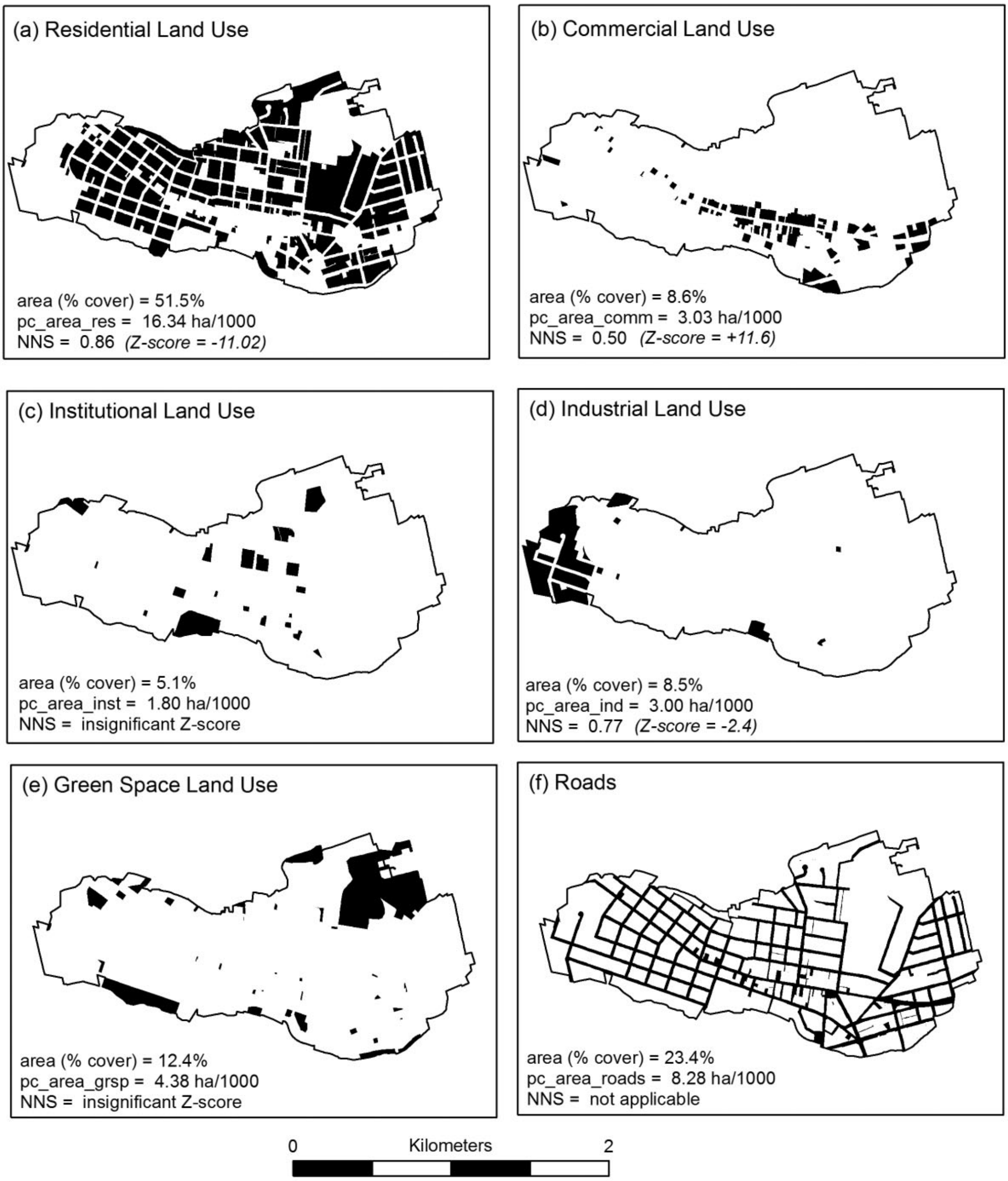

Figure 4 Spatial distribution of land-use parcels in the Dundas study neighbourhood and the related values of variables measuring percentage and per capita land-use fractions and the degree of clustering of land-use types (where applicable)

Owens 1993) and a concentration of convenience stores in only a few locations. Strathcona provides better pedestrian access to a somewhat more dispersed pattern of stores, and the higher population density supports a greater number of convenience stores (thereby improving access). Sub-index results suggest a moderate degree of access for the two suburban neighbourhoods and moderate-to-good access for the two urban

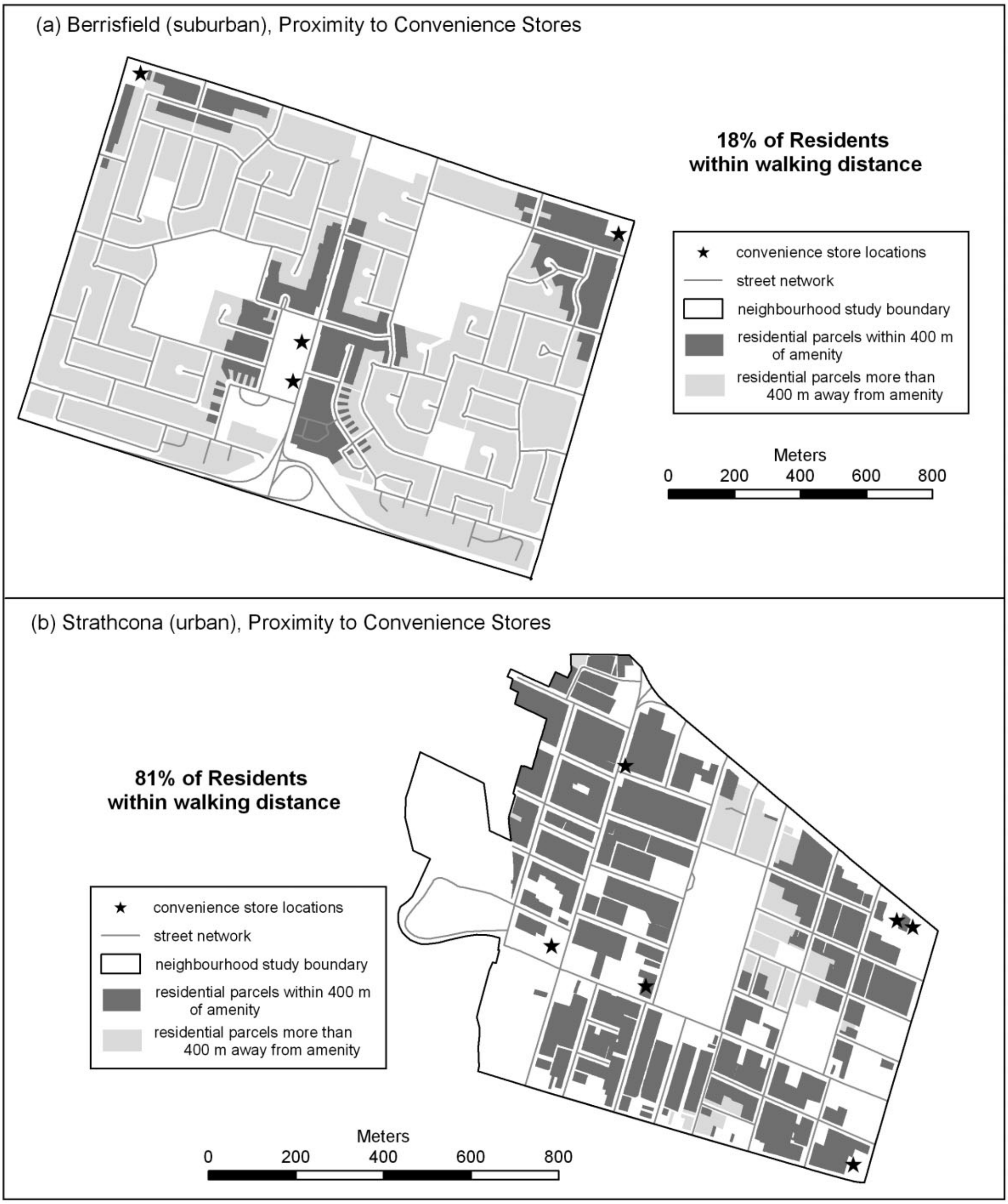

Figure 5 Proximity of neighbourhood residential parcels to convenience stores in the Berrisfield suburban and Strathcona urban neighbourhoods

Note: Strathcona has 81% of its residential parcels within 400 m of the nearest convenience store versus only 18% for Berrisfield. All proximity analyses have measured route distances using the depicted street network neighbourhoods (Table 8). These results agree well with the expected behaviour of suburban versus urban neighbourhoods, in which urban street patterns fare much better in providing better pedestrian access (Hess 1997; Southworth 1997).

Conclusions

This paper has presented a conceptual GIS-based model quantifying the concept of land-use diversity. Land-use diversity within a residential neighbourhood was defined as having four key characteristics, including a mix of land-use types, a mix of housing types, a mix of amenities and sufficient walking distance proximity to commonly sought amenities. The LDI model is comprised of four equally weighted sub-indices in which one sub-index is developed for each of these key characteristics.

The application of the LDI model to four residential neighbourhoods represents an initial model calibration. Overall, the urban residential neighbourhoods outperformed the suburban ones, supporting previous research that traditional urbanism represents a more sustainable form of residential development (Duany *et al.* 2000; Barton *et al.* 2003; Gordon and Vipond 2005; Smart Growth British Columbia 2014), and that mixed and compact urban forms are preferred for a variety of reasons (Clifton *et al.* 2008). The LDI model will be strengthened in future research as more case study applications are considered to more fully capture the possible range of urban and suburban neighbourhood conditions. In addition, future versions of the model will benefit from more precise knowledge of the desired target conditions and a refinement of the weighting factors. In the conceptual version of the model, it had been hoped to develop an absolute measure of land-use diversity, one in which each of the included criteria are weighed against some well-defined condition of urban sustainability. This comparison to well-defined sustainability criteria was achieved for a number of variables included, particularly those relating to proximity analyses in sub-index 4 and especially access to transit. However, several variables within the LDI model lack a definitive 'sustainability target value', including a target for residential density, and hence rely on a relative approach for comparing one neighbourhood with another. Despite these limitations, the LDI model is a useful evaluation tool for measuring conditions of greater sustainability at the neighbourhood scale. In addition, Talen (2003) and Clifton *et al.* (2008) argued for the better and more standardised evaluation of emerging urban forms like neo-traditional design and smart growth, so that they become more tangible and, therefore, more applied concepts. The LDI model was developed with this 'applied' aspect in mind. The input variables are not overly complex calculations and the interpretation of their physical meanings is well-linked to concepts that professional planners and other practitioners work with on a regular basis. It is anticipated the LDI model will assist jurisdictions who are planning new, and reconfiguring old, neighbourhoods that better meet the criteria of more sustainable neighbourhood forms.

Acknowledgements

Funding for this research was provided by Canada's Social Sciences and Humanities Research Council and Natural Sciences and Engineering Research Council. Assistance from various undergraduate research assistants, notably Cameron Smith, is gratefully acknowledged during data collection as is that from Heather Tompkins and Christine Shultis during the development of several key GIS procedures in the LDI model. Advice concerning neighbourhood selection from city planners in Thunder Bay (Leslie McEachern) and Hamilton (Vanessa Grupe) is also very much appreciated. The digital spatial data was generously provided by the two cities with technical support from Richard Paola (Hamilton) and Janice Bonish (Thunder Bay); without these datasets, the project would not have been possible. We also thank the two anonymous referees whose comments have improved the manuscript.

References

Atash F 1994 Redesigning suburbia for walking and transit: emerging concepts *Journal of Urban Planning and Development* 120 48–57

Barton H, Grant M and Guise R 2003 *Shaping neighbourhoods: a guide for health, sustainability and vitality* Spon, London

Beatley T 2000 *Green urbanism: learning from European cities* Island Press, Washington DC

Benfield F K, Raimi M D and Chen D D T 1999 *Once there were greenfields: how urban sprawl is undermining America's environment, economy, and social fabric* Natural Resource Defense Council, Washington DC

Calthorpe P 1993 *The next American metropolis: ecology, community and the American dream* Princeton Architectural Press, New York

Clifton K, Ewing R, Knaap G-J and Song Y 2008 Quantitative analysis of urban form: a multidisciplinary review *Journal of Urbanism* 1 17–45

Duany A, Plater-Zyberk E and Speck J 2000 *Suburban nation: the rise of sprawl and the decline of the American dream* North Point Press, New York

ESRI 2009 ArcGIS desktop help description of 'Nearest Neighbour Statistic', ArcGIS software version 9.2 Environmental Systems Research Institute Inc., Redlands CA

Ewing R 1997 Is Los Angeles-style sprawl desirable? *Journal of the American Planning Association* 63 107–26

Ewing R, Pendall R and Chen D 2002 Measuring sprawl and its impact Smart Growth America (http://www.smartgrowthamerica.org/sprawlindex/sprawlindex.html/) Accessed 27 April 2014

Ewing R, Schmid T, Killingsworth R, Zlot A and Raudenbush S 2003 Relationship between urban sprawl and physical activity, obesity, and morbidity *American Journal of Health Promotion* 18 47–57

Frank L D, Schmid T L, Sallis J F, Chapman J and Saelens B E 2005 Linking objectively measured physical activity with objectively measured urban form *American Journal of Preventive Medicine* 28 117–25

Frenkel A and Ashkenazi M 2008 Measuring urban sprawl: how can we deal with it? *Environment and Planning B* 35 56–79

Gordon D and Vipond S 2005 Gross density and New Urbanism: comparing conventional and New Urbanist suburbs in Markham, Ontario *Journal of the American Planning Association* 71 41–54

Hess P M 1997 Measures of connectivity *Places* 11 59–65

Hofmann V 2006 Residential infill alternatives for the Interocean Park neighbourhood, Thunder Bay, Ontario Unpublished HBES thesis Department of Geography, Lakehead University

Jacobs J 1961 *The death and life of great American cities* Random House, New York

Katz P 1994 *The new urbanism* McGraw-Hill, New York

Knaap G-J, Song Y and Nedovic-Budic Z 2007 Measuring patterns of urban development: new intelligence for the war on sprawl *Local Environment* 12 239–57

Millward H and Bunting T 2008 Patterning in urban population densities: a spatiotemporal model compared with Toronto 1971–2001 *Environment and Planning A* 40 283–302

Munro K 2004 Does it pay to maintain New Urbanist infrastructure? A fiscal comparison of alternative community forms *Plan Canada* 44 25–8

Province of Ontario 2006 *Places to grow: growth plan for the Greater Golden Horseshoe* Ontario Ministry of Public Infrastructure Renewal, Queen's Printer for Ontario

Pushkarev B S and Zupan J M 1982 Where transit works: urban densities for public transportation in **Levinson H S and Weant R A** eds *Urban transportation: perspectives and prospects* Eno Foundation, Westport CT 341–4

Randall T A 2008 Preferences of suburban residents in Thunder Bay, Ontario towards neighbourhood intensification and rediversification *Canadian Journal of Urban Research* 17 28–56

Randall T A and Baetz B W 2001 Evaluating pedestrian connectivity for suburban sustainability *Journal of Urban Planning and Development* 127 1–15

Schwarz N 2010 Urban form revisited – selecting indicators for characterizing European cities *Landscape and Urban Planning* 96 29–47

Smart Growth British Columbia 2014 Smart growth principles (http://www.smartgrowth.bc.ca/AboutUs/SmartGrowthPrinciples/tabid/133/Default.aspx) Accessed 15 April 2014

Southworth M 1997 Walkable suburbs? An evaluation of neo-traditional communities at the urban edge *Journal of the American Planning Association* 63 28–44

Southworth M and Owens P M 1993 The evolving metropolis: studies of community, neighbourhood, and street form at the urban edge *Journal of the American Planning Association* 59 271–88

Speir C and Stephenson K 2002 Does sprawl cost us all? Isolating the effects of housing patterns on public water and sewer costs *Journal of the American Planning Association* 68 56–70

Statistics Canada 2002 *Census of Canada for 2001: Census metropolitan areas and census agglomerations with components* Minister of Supply and Services, Ottawa

Statistics Canada 2007a *2006 Census of Canada: Census metropolitan areas and census agglomerations with components* Minister of Supply and Services, Ottawa

Statistics Canada 2007b *North American industry classification system* Catalogue no. 12-501-XIE Ministry of Industry, Ottawa, Canada

Talen E 2003 Measuring urbanism: issues in smart growth research *Journal of Urban Design* 8 195–215