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

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

<table>
<thead>
<tr>
<th>LDI model sub-index</th>
<th>Characteristic of residential development (this study)</th>
<th>Corresponding Principle of Smart Growth (see Smart Growth BC 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The diversity of land uses and the degree to which they are mixed</td>
<td>(Principle 1) Mix land uses. Each neighbourhood has a mixture of homes, retail, business and recreational opportunities</td>
</tr>
<tr>
<td>2</td>
<td>The diversity of housing types and the degree to which they are mixed, implying a mixed socio-economic population as well</td>
<td>(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</td>
</tr>
<tr>
<td>3</td>
<td>The range of goods and services that are present within the neighbourhood</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>The proximity of a neighbourhood’s residents to some key fundamental neighbourhood amenities or services</td>
<td>(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</td>
</tr>
</tbody>
</table>

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 based on 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 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.
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).

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

(1)

where \( S_i \) = standardised value for variable \( i \); \( X \) = original values 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
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

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

<table>
<thead>
<tr>
<th>Variable ID</th>
<th>Description</th>
<th>Units</th>
<th>Sprawl condition</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>pc_area_res</td>
<td>Per capita residential land (ha per 1000 population)a</td>
<td>ha/1000</td>
<td>Higher values; lot sizes are larger, and more detached dwellings with bigger yards are present in suburban neighbourhoods</td>
<td>10%</td>
</tr>
<tr>
<td>pc_area_comm</td>
<td>Per capita commercial land (ha per 1000 population)a</td>
<td>ha/1000</td>
<td>Lower values; there are fewer non-residential activities in a suburban versus urban residential neighbourhood</td>
<td>10%</td>
</tr>
<tr>
<td>pc_area_inst</td>
<td>Per capita institutional land (ha per 1000 population)a</td>
<td>ha/1000</td>
<td>Residual area is lower, and there are fewer non-residential activities per area</td>
<td>10%</td>
</tr>
<tr>
<td>pc_area_ind</td>
<td>Per capita industrial land (ha per 1000 population)a</td>
<td>ha/1000</td>
<td>Higher values; suburban neighbourhoods on the periphery of cities have a greater area of public green spaces like parks, riverine corridors, etc.</td>
<td>10%</td>
</tr>
<tr>
<td>pc_area_grsp</td>
<td>Per capita green space (ha per 1000 population)a</td>
<td>ha/1000</td>
<td>Higher values; suburban neighbourhoods on the periphery of cities would have a greater area of public green spaces like parks, riverine corridors, etc.</td>
<td>10%</td>
</tr>
<tr>
<td>pc_area_roads</td>
<td>Per capita road area (ha per 1000 population)a</td>
<td>ha/1000</td>
<td>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</td>
<td>10%</td>
</tr>
<tr>
<td>cl_res_pcls</td>
<td>Clustering of residential area parcelsb,c</td>
<td>–</td>
<td>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</td>
<td>15%</td>
</tr>
<tr>
<td>cl_comm_pcls</td>
<td>Clustering of commercial area parcelsb,c</td>
<td>–</td>
<td>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</td>
<td>15%</td>
</tr>
</tbody>
</table>

---

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.

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

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

<table>
<thead>
<tr>
<th>Variable ID</th>
<th>Service category</th>
<th>Types of amenities included in the service category</th>
<th>Units</th>
<th>Sprawl condition</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>pc_pers_gs</td>
<td>Personal goods and services</td>
<td>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)</td>
<td>#/1000</td>
<td>lower values; sprawl typically lacks neighbourhood amenities or has a very small number of these; a functioning main street retail, like that found in Dundas, Ontario – by contrast – has a considerable number of amenities in these goods and services categories</td>
<td>15%</td>
</tr>
<tr>
<td>pc_house_gs</td>
<td>Household goods and services</td>
<td>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)</td>
<td>#/1000</td>
<td></td>
<td>7.5%</td>
</tr>
<tr>
<td>pc_health_gs</td>
<td>Healthcare goods and services</td>
<td>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.</td>
<td>#/1000</td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td>pc_protech</td>
<td>Professional and technical services</td>
<td>Includes real estate, legal, accounting, engineering, consulting and other professional services</td>
<td>#/1000</td>
<td></td>
<td>7.5%</td>
</tr>
<tr>
<td>pc_govt</td>
<td>Government services</td>
<td>Includes police/fire protection services, and municipal and provincial government offices</td>
<td>#/1000</td>
<td></td>
<td>7.5%</td>
</tr>
<tr>
<td>pc_inst</td>
<td>Institutional facilities</td>
<td>Includes libraries, elementary and secondary schools, hospitals, universities and colleges, and religious organisations</td>
<td>#/1000</td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td>pc_tourrec</td>
<td>Tourism, entertainment and recreation</td>
<td>Includes travel agencies, museums, hotels/motels, fitness centres, community centres and other tourist and recreational services</td>
<td>#/1000</td>
<td></td>
<td>7.5%</td>
</tr>
<tr>
<td>pc_food_sales</td>
<td>Food and beverage retail</td>
<td>Includes supermarkets, convenience stores, beer and liquor stores</td>
<td>#/1000</td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td>pc_food_serv</td>
<td>Food services</td>
<td>Includes restaurants, bars, pubs</td>
<td>#/1000</td>
<td></td>
<td>7.5%</td>
</tr>
<tr>
<td>pc_transpo_gs</td>
<td>Transportation goods and services</td>
<td>Includes taxi services, auto maintenance and repair, auto rental and parking lots</td>
<td>#/1000</td>
<td></td>
<td>7.5%</td>
</tr>
</tbody>
</table>

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. Each of these goods and services categories is standardised to the neighbourhood population. Variable units are the number of amenities present per 1000 population. 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. 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.
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 (CMAs) (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

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

<table>
<thead>
<tr>
<th>Variable ID</th>
<th>Description</th>
<th>Units</th>
<th>Sprawl condition</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>rtedis_supmkt</td>
<td>Proximity to supermarkets (average route distance from each dwelling unit to nearest supermarket)</td>
<td>m</td>
<td>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)</td>
<td>12.5</td>
</tr>
<tr>
<td>rtedis_conv</td>
<td>Proximity to convenience stores (average route distance from each dwelling unit to nearest convenience store)</td>
<td>m</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>rtedis_busstop</td>
<td>Proximity to transit (average route distance from each dwelling unit to nearest bus stop)</td>
<td>m</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>rtedis_elemsch</td>
<td>Proximity to elementary schools (average route distance from each dwelling unit to nearest elementary school)</td>
<td>m</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>pc_supmkt</td>
<td>% of dwelling units within 400 m of supermarkets</td>
<td>%</td>
<td>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)</td>
<td>12.5</td>
</tr>
<tr>
<td>pc_conv</td>
<td>% of dwelling units within 400 m of convenience stores</td>
<td>%</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>pc_busstop</td>
<td>% of dwelling units within 400 m of bus stops</td>
<td>%</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>pc_elemsch</td>
<td>% of dwelling units within 400 m of elementary schools</td>
<td>%</td>
<td>12.5</td>
<td></td>
</tr>
</tbody>
</table>

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 ‘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. 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.
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)
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 that the communities 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 communities 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 that 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).

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

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

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)
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.
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 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)
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 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)

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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.

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