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A transboundary study of urban sprawl in the Pacific Coast region of North America: The benefits of multiple measurement methods

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Abstract

Sprawling urban development has emerged as a primary concern of policy makers, land preservationists and both urban and rural communities in developing regions across the globe. For the first time in history, more global residents lived in urban areas than not and the trend to urbanization is in full force at the start of the 21st century. An understanding of the nature and character of urban sprawl is complicated by a failure to satisfactorily define it and by the limitations of measurement techniques designed to characterize complex landscape forms. Like other landscape patterns, the quantification of urban sprawl is highly spatially and temporally scale-dependent. This paper summarizes a recent project to measure urban sprawl in the transboundary region of the Pacific Coast of North America. The metropolitan centers of Portland, OR, Seattle, WA and Vancouver, BC, span two nations, three state/provincial governments and dozens of cities. As a region, this was a global leader in population growth in the 1990s. The study relied on three separate methods – an impervious surface metric, a neighborhood density metric and a building permit metric – for quantifying urban growth. The results provide insight on the strengths and shortcomings of different methods with respect to the challenges posed by data availability and format. Taken together they demonstrate the richer understanding that combined methods may offer in characterizing phenomena as difficult to communicate and agree upon as urban sprawl.

Keywords: Urban sprawl; GIS; Transboundary; Pacific Northwest

1. Introduction

In the US, urban sprawl is a much discussed though poorly defined phenomena (Ewing, 1994). More often it's described qualitatively rather than defined quantitatively (Chin, 2002; Daniels, 1998). Sprawl is usually characterized by auto-centered, low-density communities that consume large amount of space per capita. Sudhira et al. (2003) define sprawl as ‘‘when the rate of the development of land outstrips the rate of population growth’’. This definition leaves open the question of scale. As Torrens and Alberti (2000) note, density-focused definitions invite further argument over the appropriate aggregation unit: should the population growth/land consumption ratio be calculated at the scale of towns, cities, enumeration units or pixels? Fulton et al. (2001) partly overcome this problem in a large nation-wide study of US cities. They define sprawl in spatially explicit terms: ‘‘if land is being consumed at a faster rate than population growth, then a metropolitan area can be characterized as sprawling’’.

The pressure to characterize and understand the dynamics behind urban sprawl stems, in part, from a worldwide trend towards increasing urbanization.

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Whereas less than 30% of the global population lived in urban settings in 1950, nearly 50% do so today. This trend has created an imperative among planners concerned with resource management, environmental health and sustainability to devise strategies to mitigate the impacts of this transition.

Several issues help explain the problems these efforts face. First, an accepted and widely used definition of sprawl remains elusive (Theobald, 2001). A consequence of this lack of consensus is that researchers have had difficulty comparing varying measurement approaches. Numerous attempts have been made to develop comparative metrics of sprawl at the national scale in the US (El Nasser and Overberg, 2001; Fulton et al., 2001; Rickets and Imhoff, 2003). The breadth of methods and inconsistency of findings testifies to the variety of perspectives on the nature of sprawl and how best to quantify it. Many definitions and analysis methods focus on measures of population density. However, purely density-based analyses may fail to distinguish between the "sprawling" nature of declining rust belt cities of the American Mid-West and the fast growing cities of the south. That is, they mistake cities losing population for sprawling (Kolankiewicz and Beck, 2001). The problem reveals one of the shortcomings of a density-based sprawl metric. Another involves the second major problem facing sprawl measurement efforts: the complicated influence of scale.

Theobald (2001) addresses scale problems when he offers a compelling critique of land use change studies that rely heavily on geographically broad and spatially discrete urban areas defined by agencies like the Census Bureau or the Natural Resource Conservation Service in the US. These studies fall short in capturing changes in the exurban rural fringe, defined as that area within 5–50 miles of a city and characterized by scattered, low-density development (Daniels, 1998). Relying on large urban areal units defined at the national scale, such studies are likely to mask land use change at the exurban and rural fringe where new, low-density development grows at the fastest rate (Theobald, 2001).

A related third problem involves the influence of spatial and temporal resolution of available data in comparative studies. Studies that attempt to compare areas in transboundary regions (regions characterized by metropolitan centers that span international borders) may be constrained by the need to resolve data management regimes of multiple jurisdictions. In these cases, many analyses utilize remotely sensed imagery (Imhoff et al., 2000; Sudhira et al., 2003; Sutton, 2003). These have the benefit of deriving from widely available datasets and allowing researchers to overcome data inconsistencies across political borders in transboundary areas. They too may be hindered in precisely the regions where an accurate measure of urban growth is necessary to quantify sprawl. Sutton's assessment (2003) relies on the brightness of nighttime lights to map the urban footprint for comparison to population. But the analysis tends to omit rural areas were light thresholds are low but population growth may be proportionately large.

This paper describes an effort to overcome the challenges outlined above by applying multiple measurement approaches in a transboundary study of urban sprawl. A transboundary region was selected in part to test how well data and methods may be reconciled across jurisdictional borders where regions in separate countries are under similar and related growth pressures. The paper evaluates whether three separate analytical techniques may, when used together, surmount the unique scale and data problems associated with sprawl measurements. The three methods utilized in this assessment are:

An impervious metric—compares impervious surface change estimates derived from satellite imagery to population change data derived from census information.

Neighborhood metric—uses a variation on population density change analysis to assess the change in transit-friendly development as defined in literature on public transit viability.

Permit metric—evaluates the trends in permitted building activities in and outside of areas designated for development.

2. Study area—regional focus

The north–south corridor connecting Vancouver, BC, to Portland, OR, spans 450 km. It crosses two countries, three state/provincial governments, dozens of large and mid-sized cities including the Seattle–Tacoma metropolitan area, and thousands of kilometers of unincorporated land under the jurisdiction of more than 30 county governments (Lewis, 2001). Fourteen and a half million people call this region (Fig. 1) home.

Economic vitality, temperate climate, and stunning scenery led the cities of the North American Pacific Coast to be recognized as some of the most liveable in North America. As a result, population growth has been significant. Since 1990, regional population grew at twice the national rate. Along the corridor formed by Interstate five connecting each of the region's major cities, the total population of the major cities doubled since 1965. From 1990 to 2000, Puget Sound, Portland

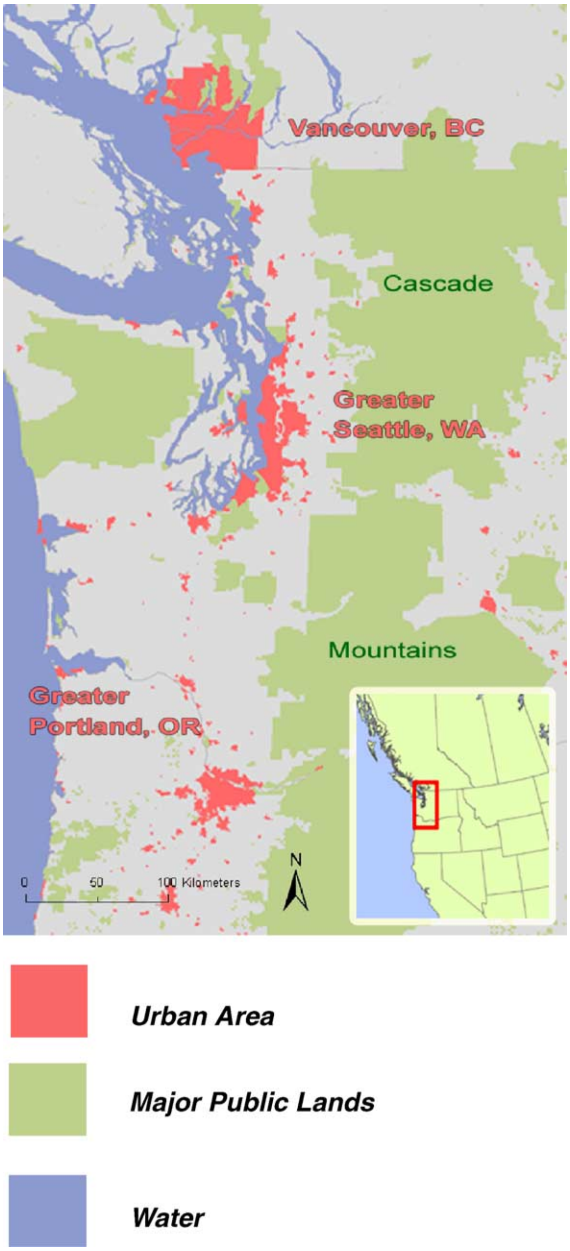


Fig. 1. The Pacific corridor—major cities, Puget Sound and Georgia Strait and the Cascade Mountains.

and Vancouver, BC, saw relatively similar, though extraordinary, annual rates of population growth, 1.9, 2.7 and 2.6%, respectively (Vancouver is measured using data dating to 1985 due to a different census schedule in Canada). On a global measure, this puts Vancouver and Portland just behind Karachi, Pakistan and New Delhi, India and just above Cairo, Egypt in growth rates of world cities for the same period (Durning et al., 2002).

Geographic constraints exacerbate the land use pressures created by dramatic population growth. From Vancouver, BC, to the southern tip of the Seattle–Tacoma–Olympia metropolis, the region is bounded by Puget Sound and the Georgia Strait, natural barriers that limit growth to the west. To the east, some 50–80 km from the urban centers, the Cascade Mountains stretch from British Columbia to Oregon. Comprising mostly public lands and alpine terrain, they form an eastern barrier that helps contain urban growth in the lowland trough.

While regional geography may ultimately place limits on the extent of urbanization, today the region's rural fringe still comprises a blend of working timber lands, farmlands and open space. In addition to contributing to the regional character prized by many of the region's inhabitants, these resource lands provide numerous ecological services (Mazza and Footer, 2000), in particular habitat for the region's endangered icon, the Pacific Salmon.

3. Data

The three methods described in the following section utilized a number of different spatial datasets, some of which required significant pre-processing and preparation. These include.

3.1. Satellite imagery: sources and pre-processing

Imagery was obtained from a variety of sources including the Global Land Cover Facility web site and USGS. Processing steps are described below. Image sources included:

Landsat Thematic Mapper$^{\text{TM}}$; August, 1989; Path 046 Row 027 (Puget Sound region)
Landsat Thematic Mapper$^{\text{TM}}$; July, 1999; Path 046 Row 027 (Puget Sound region)

Landsat Thematic Mapper$^{\text{TM}}$; August 1989; Path 050 Row 028 (Portland Metropolitan region)
Landsat Thematic Mapper$^{\text{TM}}$; August 1999; Path 050 Row 028 (Portland Metropolitan region)

ETM+ date 1999; August 1987; Path 47 Row 26 (Greater Vancouver region)
ETM+ date 1999; August 1999; Path 47 Row 26 (Greater Vancouver region)

Prior to any analysis of remotely sensed data, several image processing steps were performed. Image registration aligns image pixels to ancillary map data and allows for time series analysis or change detection. Pixel calibration accounts for atmospheric and instrument effects to the recorded signal. Finally, a terrain correction normalizes the effect of differences in illumination due to topography.

For each of the three scene locations, census block data, roads data and shaded relief from elevation data were used to geographically register primary images (circa 1990). Secondary images (circa 2000) were registered to primary images with less than 1 pixel root mean squared error in over 100 control points per image.

For our study, the purpose of pixel calibration was to remove additive effects introduced by atmospheric scatter and instrument offset at the sensor. Multiplicative effects (gain introduced by the atmosphere and at the sensor) were ignored as our intention was not to perform any image classification using reference spectra. A simple dark object subtraction was carried out to compensate for additive effects to the data.

Though each of our scene locations included areas with significant topographic relief, we determined that a terrain correction was not warranted. Because our image acquisition dates were chosen to minimize differences in sun position, and because our study areas within each scene were concentrated in areas of relatively flat topography, we concluded that normalizing differences in illumination would not significantly improve results.

After completing initial image correction for each of the three image pairs, image endmembers were selected to represent signatures from vegetated, non-vegetated and shaded pixels. An iterative process involving examination of pixel spectra distribution, trial endmember selection, image unmixing and examination of test results was used to determine the final selection of image endmembers. After producing three final fraction images corresponding to the three endmember proportions for each of the image pairs, the impervious metric was calculated as follows:

$$\mathrm{IM} = \frac{f_{\mathrm{V}}}{f_{\mathrm{V}} + f_{\mathrm{N}}}$$

where f_{V} is the fraction representing the vegetated portion and f_{N} is the fraction representing the non-vegetated portion. This assumes that the shaded portion of each pixel comprises the same ratio of vegetated to non-vegetated material as the unshaded portion.

3.2. Census data: sources and pre-processing

US Census Data 1990—block group level population data obtained from US Census Bureau via Factfinder

US Census Data 2000—block group level population data obtained from US Census Bureau via Factfinder

Canadian Census data for 1986, 1991 and 1996 obtained from StatCan

To prepare census data for use in the delineation of neighborhoods that would be used to measure sprawl, several transformations were made. First, population data taken from the census files for each area were converted from vector to grid format. This enabled us to apply an algorithm that delineated neighborhoods of various pre-set densities by summarizing population data summarized by pixel (Fig. 1). We used a 30 m pixel grid to match the lattice created by the elevation and remote sensing data. Using ancillary spatial data, including water bodies and other features that preclude human settlement in each of the study areas, uninhabitable areas within and across census block group boundaries were identified and mapped (Fig. 2). Population data were then removed from these areas and transferred into habitable pixels. This technique, known as dasymetric mapping, uses spatial analysis techniques to report or analyze variable data at a smaller enumeration unit than the one at which it is collected (Holloway et al., 1997). In this case, the resulting population dataset provides a more spatially refined and finer grained map of population distribution (Torrens and Alberti, 2000) in each of the major metropolitan areas and their outlying regions (Fig. 3).

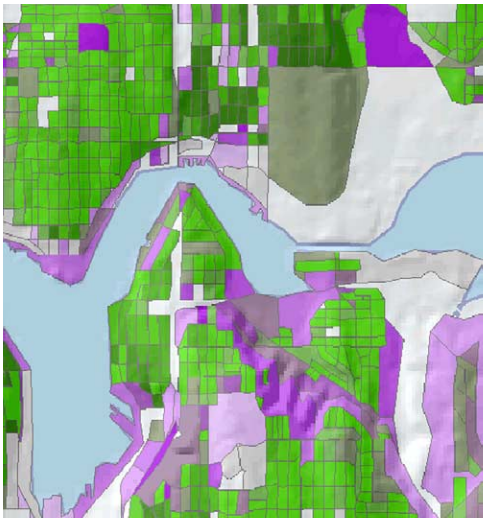


Fig. 2. Population count grid from census blocks.

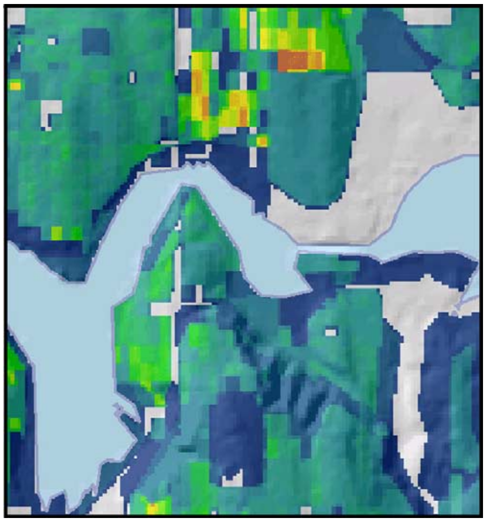


Fig. 3. Results of depopulating uninhabited areas.

3.3. Permit data: sources

Portland building permit records—obtained from Portland Metro, 1995–2001

Puget Sound building permit records—obtained from the Puget Sound Regional Council, 1991–2001

No permit records were available for the entire Greater Vancouver Regional District. It was deemed too expensive to obtain and reconcile permits from each of the many jurisdictions within the GVRD, consequently Vancouver, BC, was excluded from the permit analysis.

The aim of the permit metric was to evaluate the pattern of new building activities in the metropolitan and surrounding regions. Building permits were screened to ensure they represented actual and not just applied for construction of new homes or commercial centers. They were geocoded by matching parcel identification numbers in the permit records to digital parcel files provided by county assessor's offices throughout each of the regions in the study area. Geocoding allowed annual permit patterns to be evaluated in a GIS. Permit locations were plotted relative to various jurisdictions and in particular with designated "urban growth areas" geographical boundaries established by regional authorities to contain the majority of new development close to existing urban centers.

4. Methods

We developed the following three metrics to characterize and measure sprawl as defined by Torrens and Alberti (2000) and Fulton et al. (2001).

4.1. Impervious metric

This approach started from the assumption that urban sprawl is fundamentally defined as a relationship between population and the built-up environment. Human development typically converts native vegetation to impervious surfaces, including pavement, buildings, even heavily graded vegetation such as lawns, which behave hydrologically like impervious surface (May et al., 2000). Impervious surface has been implicated in a variety of ecological ills, including the degradation of stream habitat, the pollution of surface waters and the raising of air and water temperature (Booth and Jackson, 1997; Booth, 2000).

Growth intended to minimize sprawl would limit the amount of impervious surface created with the influx of new residents to a region. By converse, sprawling regions would add impervious surface at a rate that exceeds the concurrent rate of population growth. By mapping the change in impervious surfaces using remotely sensed data and comparing population density changes over the same time scale, the impervious metric aims to measure sprawl by calculating the change in the amount of built surface per capita.

A principal challenge to this method involves the calculation of impervious surface using remotely sensed data. Remote sensing analysis is frequently utilized in the calculation of landscape metrics (Gustafson, 1998). Indices of heterogeneity, patchiness, contagion and fractal analysis have each been applied by different researchers in an attempt to characterize the physical characteristics of sprawling landscapes (Torrens and Alberti, 2000; Clapham, 2003). But impervious surfaces are notoriously difficult to measure using remote sensing techniques. The image elements that comprise urban landscapes are highly heterogeneous. The spectral reflectance of materials in rooftops, parking lots, streets and sidewalks, all of which are impervious may be dramatically different. This makes the automated identification of impervious surfaces in an image difficult.

In a concentrated effort to resolve this difficulty, this analysis utilized a technique known as spectral mixing analysis (SMA). SMA is a physically based image analysis process that supports repeatable and accurate extraction of quantitative sub-pixel information (Smith and Ustin, 1990; Adams and Smith, 1993). This method presumes that the spectral variability in a multi-spectral image can be modeled by mixtures of a small number of surface materials with distinct reflectance spectra (Adams et al., 1989). Unlike supervised and unsupervised image classification, SMA does not rely on the detection or identification of pixel clusters with similar reflectance spectra; rather it considers each pixel individually and assesses the presence and proportion of select endmembers—representative pixels whose spectral signatures are used to train the model to identify sub-pixel proportions of impervious surface. SMA produces fraction images that are pixel by pixel measures of the percent composition for each endmember in the spectral mixing model. Fraction images produced with SMA have been shown to be effective in mapping natural environments (Smith and Ustin, 1990) as inputs for land use change analyses (Smith and Ustin, 1990; Sabol et al., 1993; Adams et al., 1986) and are suitable inputs for ecological models (Ustin and Smith, 1993).

For this analysis, the variability of urban surfaces was treated with two endmembers that served as proxies for impervious surfaces. Several endmembers representing the varied spectral signatures of typical impervious surface were also evaluated. Input imagery for the impervious surface metric were Landsat Thematic Mapper^{TM} pairs spanning two separate years at roughly 10 year intervals and covering the metropolitan areas (see image dates, path/row identification in Section 3). Image pairs were assembled at roughly 10 year intervals in order to better associate measures of built surface with recent census data.

This technique of approximating impervious surface fractions takes advantage of the fact that development in the region is generally accompanied by removal of vegetation. To account for other processes that convert vegetation into bare land, a mask layer was created that corresponded to areas of timber harvest, agricultural activity and unpopulated areas. Further analysis excluded all areas within the mask layer.

For each scene location, the pair of impervious metric data layers was used to produce a single classification representing the state of impervious surface over the decade between image acquisition dates. Four classes were defined:

- *No impervious material*: IM less than 15% for both dates.
- *Partially impervious*: IM between 15 and 80% for both dates.
- *Fully impervious*: IM greater than 80% for both dates.
- *New impervious*: Increase from no impervious or partially impervious to a higher class.

4.2. Neighborhood metric

Sprawling communities are car-dependent communities. This too is an often re-occurring theme in the various definitions of urban sprawl in North America (Handy and Niemeier, 1997). Because they are often characterized by rigidly separated residential and commercial areas rather than by neighborhoods with amenities in walking distance, residents of sprawling communities have a higher reliance on automobiles. The neighborhood metric draws upon research on the population density at which mass transit becomes economically viable (Newman and Kenworthy, 1989). This research establishes thresholds at which communities become sufficiently dense to support local commercial services like groceries and cleaners. At less than 1 person per acre, few or no services can be expected within walking range and cars are required for any necessity from shopping, to working, or attending school. From 1 to 12 people per acre, public transportation is still not viable and residents are presumed to be car-dependent. Above 12 people per acre, public transit becomes more widespread and residents enjoy a greater density of services. Dense urban centers are characterized by population densities greater than 40 people per acre. At this level, individual auto ownership declines and alternative modes of transportation abound (Newman and Kenworthy, 1989).

To identify developed areas that fell into these categories, a two-step process involving the dasymetricaly mapped population density data (see Section 3) and the application of a convolution kernel was utilized.

We suspected that both steps would enhance the spatial precision of the population data and would effectively enhance the resolution of the data. Research suggests that dasymetric mapping may allow analysts to more accurately ‘‘see’’ the distribution of the mapped phenomena within enumeration units. This may be a particularly important attribute in areas of less concentration – i.e., rural areas – where larger census block boundaries are required to normalize data (Theobald, 2001).

The convolution kernel was then applied to the updated gridded population datasets. For each grid cell in an urban area, local population density was calculated as the density of the smallest circle that contained at least 500 residents—a rough proxy for a neighborhood. People per acre was then calculated for that neighborhood, providing a measure of neighborhood density for every location on the map. The result is a surface that was classified in four categories defined by thresholds provided by the literature (Newman and Kenworthy, 1989) relating transportation patterns to population density (Fig. 4). In addition to maps that display the change in ‘‘transit-friendly’’ development over time, statistical summaries allowed for an explicit

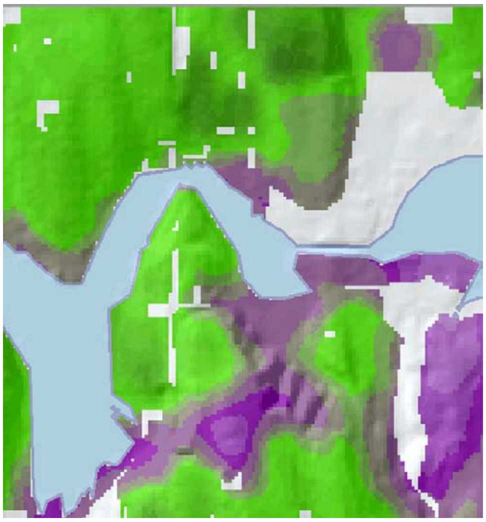


Fig. 4. Net density surface classified in transportation-related categories.

comparison of the major metropolitan regions to determine which are characterized by growth in neighborhoods incapable of supporting public transit.

4.3. Permit metric

Most of the metropolitan areas in the study area are subject to growth management regulations. Jurisdictions at both the state/provincial level and the local/county level are responsible for setting policy and implementing strategies that contain new growth within established urban growth boundaries (UGBs). UGBs are subject to revision over time, but nonetheless provide a distinct geographic reference point for measuring how well growth is being channeled. The permit metric evaluates the annual number of residential building permits for new construction. Specifically, it monitors the percentage of those occurring outside established UGBs as a way of gauging whether growth is leading to sprawl, or the infill of existing developed lands. More than any of the previously described metrics, the permit metric speaks to the impacts of day-to-day decision making at the local scale of neighborhoods and communities.

In Puget Sound and Portland, building permit data were gathered for the years of 1991–2000. Changes in data gathering policies and additional factors precluded evaluation of data older than these. No unified regional data were available for the Greater Vancouver area. The permit metric sought to identify or corroborate the patterns of sprawl revealed in the prior analyses by: (1) tallying the number of permits for new residential units within and outside of UGBs and (2) summarizing the distribution of new residential permits in each of the population density bins used in the neighborhood metric analysis.

In the US urban centers, building permit records were selected according to the criteria described in Section 3 and then geocoded and mapped. Annual statistics were compiled and maps illustrating the annual permitting activity both within and without the urban growth boundaries were developed.

5. Results

Understanding how the region is growing is an exercise in scale. When considered en masse, the trend appears positive. Thirty-two percent of the residents in the three metropolitan centers now live in compact neighborhoods, up from 27% in 1990. But examining each of the metrics at the scale of each metro region and its constituent cities reveals considerable complexity. Table 1 summarizes the findings of each metric at the scale of each metropolitan area studies.

5.1. Impervious metric

The impervious metric seeks a measurable association between population growth and new built structures. Sprawling communities, by definition, consume more land per capita than compact ones.

Table 1
Summary results of each sprawl metric by metropolitan area

	Annual population growth[a] (%)	Permit metric		Neighborhood metric		Impervious metric
		New permits inside UGB 1995 (%)	New permits inside UGB 2001 (%)	Residents in compact communities 1990 (%)	Residents in compact communities 2000 (%)	Open space converted to development (km^2)
Puget Sound	1.9	78	88	21	24	138
Greater Portland	2.7	94	95	20	25	120
Greater Vancouver	2.6	NA	NA	51	62	67

[a] Canadian annual rate calculated from 1984 to 1999.

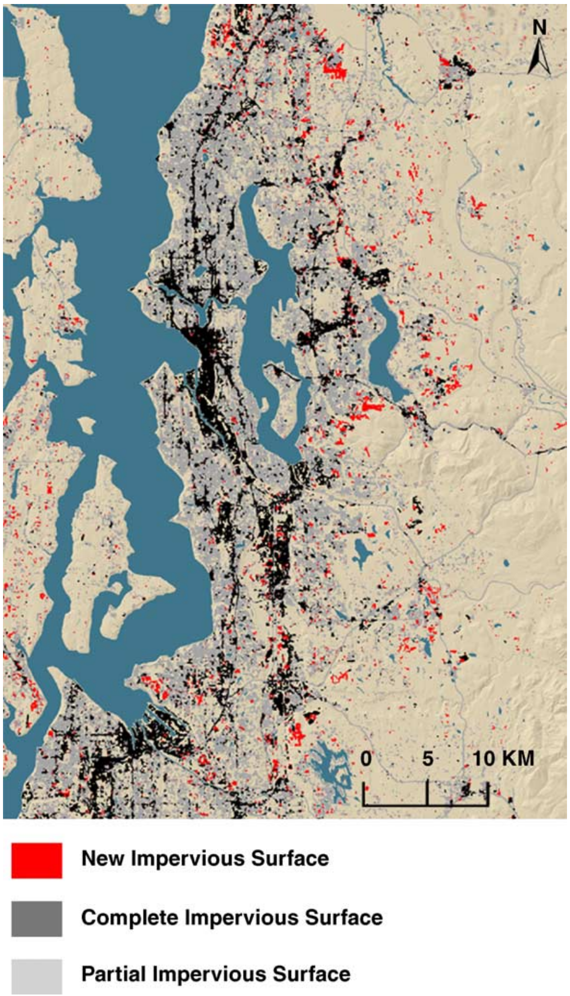


Fig. 5. New impervious surface in the Puget Sound region, 1988–1999.

Puget Sound, the metro region with the largest developed "footprint", converted 156 km^2 of undeveloped land to some level of imperviousness. The new development that occurred in the region was scattered and disconnected (Fig. 5). Some occurred along the fringes of existing developed areas, but much took place in previously undeveloped areas of the map.

Fig. 5 in Puget Sound contrasts with Fig. 6 in the Greater Portland area. Fig. 6 suggests that most of the new impervious surfaces that Portland added were closer to the already compact centers of its urban cores. In the time between the two satellite images (1988–1999), Portland's suburbs remained separated from one another by largely undeveloped land. Nevertheless, new impervious surfaces consumed 120 km of open space, most of it within the bounds of the region's defined UGBs.

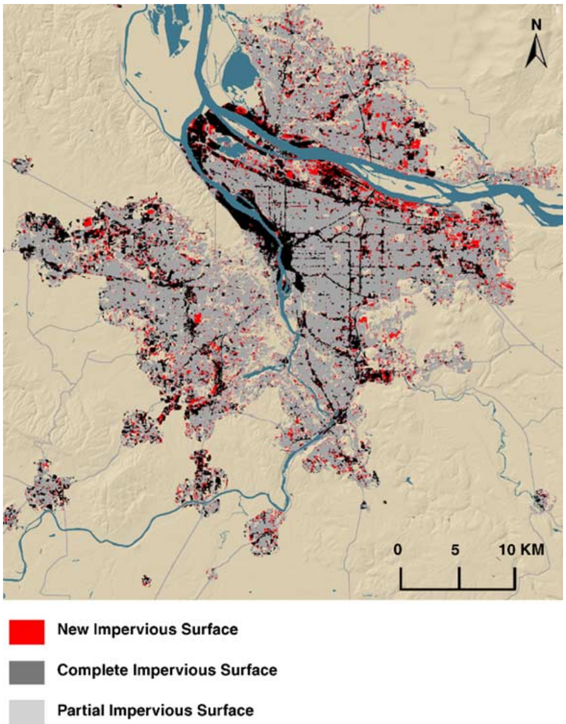


Fig. 6. New impervious surface in the Portland Metro region, 1989–1999.

Vancouver, BC, set the high standard for the region. Despite taking in the greatest percentage of new residents, Vancouver added the least amount of new impervious surface (67 km^2) during the same time. The vast majority of new impervious surface appeared along the edges of existing urban areas or as infill within those areas. Very little new impervious surface emerged in the less developed and agricultural lands surrounding Greater Vancouver.

5.2. Neighborhood metric

Using the transportation oriented population categories that are the basis of the neighborhood metric, the most sprawling region would be the metropolitan area with the greatest share of its people living in communities less than 12 people per acre.

In Puget Sound, a comparison of density maps from 1990 to 2000 reveals that 55% of the new growth or 253,000 new residents settled in low-density areas with fewer than 12 people per acre. Fig. 7 reveals a picture of scattered, low-density development punctuated by concentrations of residents throughout the nearby suburban and rural lands. Very little of the region crosses the threshold of greater than 40 people per acre. By the end of the decade, only one in four Puget Sound

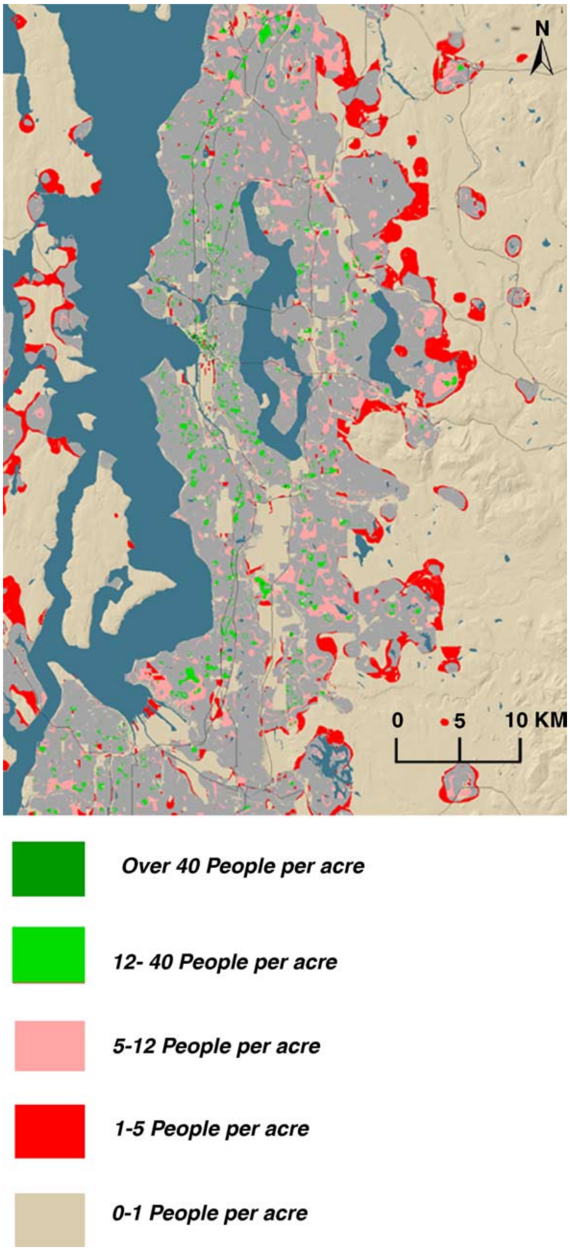


Fig. 7. Neighborhood metric—population density in Puget Sound region, 2000.

residents lived in compact communities, though this represents an improvement from 1990 when the number was one in five.

By contrast, Vancouver, BC, managed its astounding 50% population growth over the 15 years considered here with notably different results. Fig. 8 confirms that Vancouver's 2 million residents occupy far less land and reside in much more consistently compact neighborhoods than their counterparts in the Puget Sound region. By 2001, more than 60% of the city's inhabitants lived in transit-friendly areas.

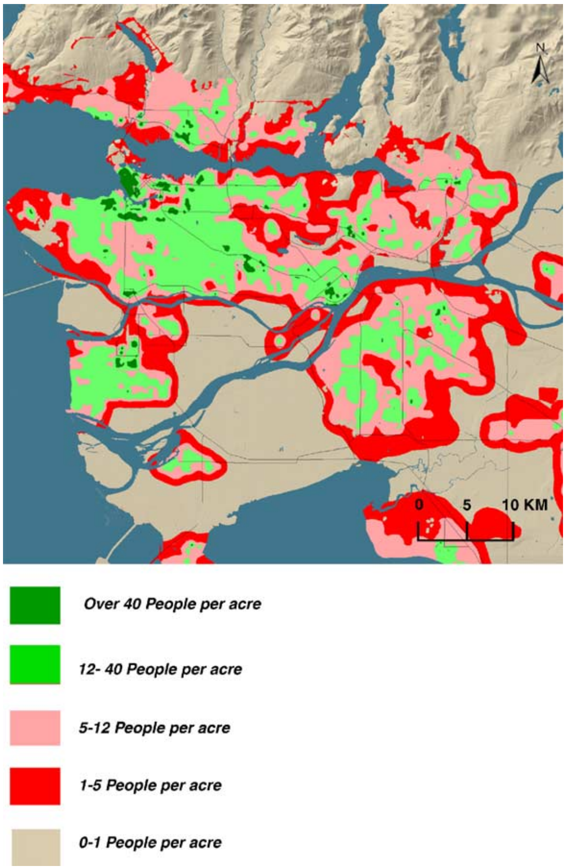


Fig. 8. Neighborhood metric—population density for Vancouver, BC, 1996.

5.3. Permit metric

Attempting to measure sprawl by analyzing the spatial distribution of new building permits helps connect the abstract phenomena of land conversion and scattered development to the day-to-day policy decisions that drive them. Population density patterns may seem out of the control of planners and land use agencies. Similarly, few jurisdictions have any mechanism for regulating impervious surfaces beyond rules for controlling stormwater at construction sites. But building permit records provide data on new construction activities at very high spatial and temporal resolution.

Fig. 9 adds context to the pattern of urban sprawl in Puget Sound that is evident in the other metrics. Forty-six thousand permits were issued outside the UGBs – represented in the screened grey area of the map – over the study period. The UGBs and the policies designed to

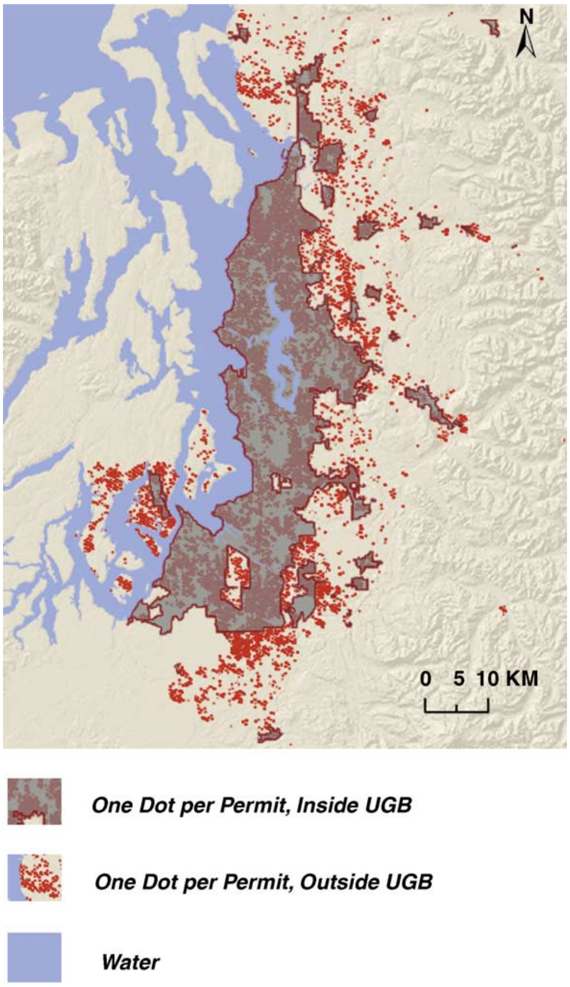


Fig. 9. Results of permit metric analysis, Puget Sound, 1991–2001.

channel growth inside them, were only established in 1995 in Puget Sound, midway through the period for which data were gathered. Nonetheless, 22,000 new permits were issued outside the boundaries even after the UGBs were created by the passing of the State Growth Management Act. Many of these may be the result of ‘‘grandfather’’ clauses, exceptions to the UGB definitions established at the time of the regulation. Looking over the entire time period, the trend in permit issuance favors more constrained growth. By 2001, 88% of the permits issued in Puget Sound were inside the UGBs, which exceeds the Regional Council’s goals and marks a dramatic improvement over earlier years.

The Portland metro placed a higher proportion of new building permits in more dense, transit-friendly areas designated for growth than the Puget Sound region was able to do. Ninety-five percent of new residential permits in Portland were issued within the UGBs,

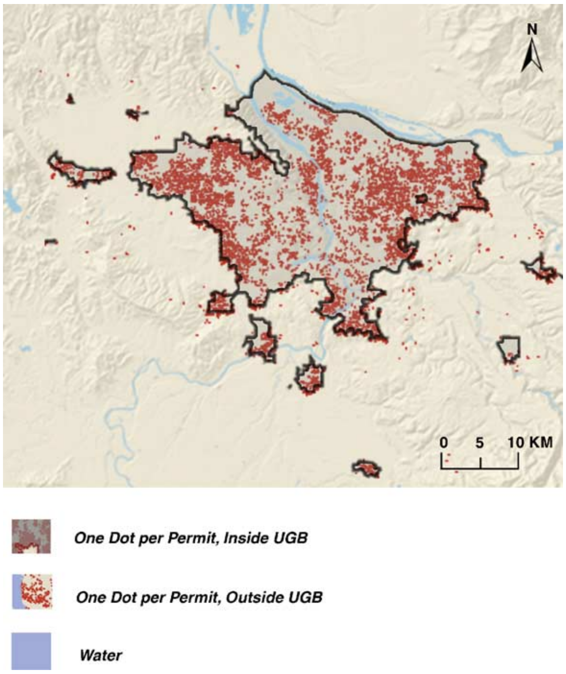


Fig. 10. Results of permit metric analysis, Greater Portland, 1995–2001.

compared to the 88% in Puget Sound. Fig. 10 provides a powerful illustration of the success achieved by Oregon Counties managing Portland growth. It clearly illustrates how few permits were issued outside urban growth designated areas for the time period studied. Data for Clark County, located in Washington State but within the range of the Portland metropolitan region, are lacking and this constitutes a significant problem, addressed below.

6. Discussion

Taken together, the metrics reveal different characteristics of the growth that transformed these regions.

Puget Sound had the highest values for each of the three metrics. That each of the three approaches ranked the same metropolitan region as the most sprawling region underscores how effectively each approach measured sprawl as it has been defined for the study. However, a more nuanced understanding emerges via a combination of the results of different metrics.

The link between policy and on-the-ground pattern is perhaps most clear with the permit metric. Unlike the construction of impervious surfaces and the density of communities, building permits are directly regulated. A shift in development-related policy that affects permit activity could be expected to have a more direct and recognizable impact on the landscape.

In the Puget Sound region, the percentage of new permits issued within the UGBs increased significantly during the latter half of this study period. By combining the georeferenced permit data with the spatial data delineating low-density neighborhoods produced by the neighborhood metric, we see that as late as 2001, 42% of the permits granted within the UGBs were issued in areas of less than 12 people per acre. This suggests that when Puget Sound's UGBs were established they included significant amounts of lower density lands to accommodate future growth.

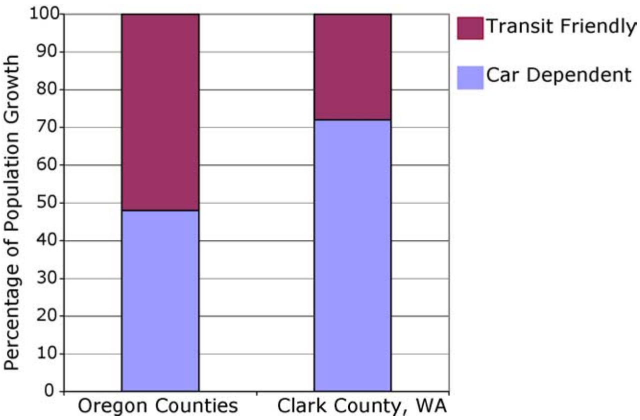
The communities of Puget Sound were only forced to take regulatory measures to address sprawl in the mid-1990s. Portland, on the other hand, has been widely recognized for the visionary land use and growth management strategies it has had in place in various forms since the 1970s. However, it is revealing to further disaggregate the data on the Portland region to put its performance in context.

The Portland metro includes Clark County, Washington, on the north bank of the Columbia River. Unlike the counties of Oregon, Clark County communities are subject to the more recently established and less stringent growth management regulations of Washington State. The results of the permit analysis suggest that Portland has grown more efficiently than Puget Sound, in spite of growing at a much faster rate. Greater Seattle grew at an annual rate of 1.9% in the study period; the Portland metro grew 2.7% annually (Northwest Environment Watch, 2004). However, significant portions of that new growth were accepted by Clark County, much of which expanded the amount of car-dependent neighborhoods (Table 2). Clark County, with its less restrictive regulatory environment, sprawled to accommodate Portland's growth. Fig. 11 illustrates 1 dot per every 10 new residents relocating to rural areas of the Portland Metro region between 1990 and 2000. Not only did Clark County, Washington, accept a disproportionately large share of the Portland metro's new residents, it located them in highly inefficient, low-density communities at a rate that eclipsed rural land consumption on the Oregon side (Fig. 11). While Portland attained admirable achievements between 1990 and 2000, channeling most of a 2.7% annual growth rate into compact neighborhoods, the metro region might have better constrained development in its rural surroundings but for Clark County's performance. Disaggregating the metro data to the constituent counties is essential to understanding the policy impact on land use efficiency in the Portland metro. Map 10 tells a story of well-contained urban development, accommodating most new growth in areas already designated for it. Map 11 reveals that that achievement may have come in part because nearby Clark County functioned as a relief valve taking pressure off Portland.

In 2004, Oregon passed Initiative 37, a controversial piece of legislation that obligates local government to compensate land owners if a land use policy restricts use or reduces property value. The effect has been to freeze growth management controls and to spawn a number of lawsuits challenging the initiative. Future analysis of sprawl and rural development will reveal whether this legislation has a demonstrable impact on the rural landscape.

In the extraordinary detail of the permit metric lies the method's shortcomings. The challenge with the

Table 2
Neighborhood metric: proportions of population growth channeled into transit-friendly development 1990–2000 in the Clark County, Washington, and Oregon Counties of the Greater Portland region



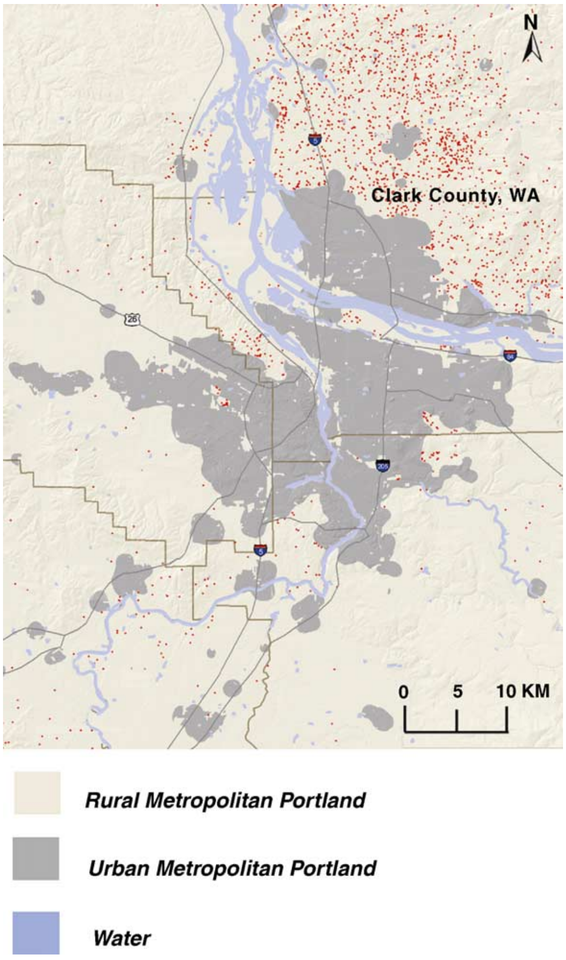


Fig. 11. Low-density development outside Portland's UGBs and in rural Clark County. One dot equals 10 new people between 1990 and 2000.

permit metric approach, as is often the case with high resolution data, is the task of managing the volumes and varieties of data across the broad geographic extent of the study area. Building permit records are a common dataset that most metropolitan planning agencies in North America maintain. However, multiple problems arise in implementing a multi-city analysis relying on these data. Local jurisdictions gather varying types of data with permits. The agencies that gather data may not be the same ones responsible for documenting, archiving and distributing them, leading to erratic gaps between the collection of data and the time that it becomes available for analysis. Additional issues arise in reconciling the meaning of data from various organizations. Does the existence of a permit confirm the project was actually built? Can new residential and commercial projects be easily and systematically separated from add-ons or re-models that do not result in the consumption of open space? Are the permits accurately georeferenced or can they be from accompanying sources? Efficient analysis across many regions depends on the existence of a regional entity that gathers and formats data from local jurisdictions, helping researchers overcome these problems. This was unfortunately not the case in Vancouver, BC, where the Greater Vancouver Regional District did not have such a policy in place. Cost and time limits thus prevented us from obtaining the necessary data from each of the governing jurisdictions in the Vancouver area and that city had to be omitted from this metric.

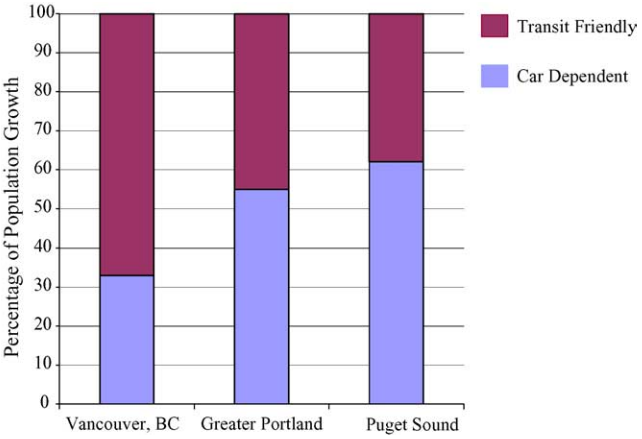
Similarly, Portland data necessarily excluded permits issued in Clark County which, because it is located in Washington State, is not formally part of Portland's metropolitan government authority. Efforts to acquire and reconcile data directly from the county and other local agencies in Clark County were unsuccessful. Instead, we used the neighborhood metric data to map density in a point form that offers some visual comparison to the permit data (Fig. 11), demonstrating the value and flexibility afforded by multiple approaches.

In contrast with the permit metric, the neighborhood metric enabled more systematic comparison of growth and density patterns across the three metropolitan regions. The neighborhood metric relies heavily on calculating change in population density and using density thresholds as a proxy for land consumption. In this case, the assumption is that a growth in the percentage of a metropolitan center that cannot support transit is a growth in car-dependent neighborhoods, a tell-tale characteristic of urban sprawl.

The method benefits from its reliance on population density analyses, which are readily understood and easy to calculate. The structure of the data lends itself to time series analyses as does the availability of historical data. Some limitations emerge in conducting the analyses across international borders in two countries with different census schedules and modeling methods. However, these are largely surmountable and do not necessarily have a significant impact on the comparability of results across borders. Like the impervious metric, the neighborhood metric is limited in its direct impact on daily decision making. Population density changes are fluid and difficult to monitor over short temporal scales. This approach relies on transit-related thresholds, which are a fairly new concept that has not apparently influenced urban planning efforts or the monitoring of growth management planning.

Table 3 provides a final summary of the findings of the neighborhood metric in the three metro regions.

Table 3
Neighborhood metric: proportions of population growth channeled into transit-friendly development 1990–2000 (Portland and Puget Sound), 1991–2001 (Vancouver, BC)



Within the context of transit-friendly development, Vancouver excels while the Puget Sound region failed to create communities dense enough to support the widespread public transportation necessary to curb sprawl. In Vancouver, BC, policies have been in place to protect surrounding agricultural lands since the early 1970s. These have successfully constrained the consumption of arable lands for commercial purposes and resulted in a more in-tact rural-agricultural landscape surrounding Greater Vancouver. Physical geography – the constraints of mountains and water – have clearly hemmed in development. But equally important and notably distinct from it US counterparts, so has a policy that has shunned the construction of significant highway systems to connect the urban core to far flung communities. Instead, a commuter transit system has grown up to support the city's growth and to provide necessary transportation for a large proportion of the communities' needs.

Of the 470,000 new residents that arrived in Puget Sound in the study period, roughly half settled in highly dense neighborhoods. In the Portland metro, population growth ranked the region near the top of the list of world cities in rate of expansion. But growth in compact neighborhoods in Portland doubled that in Seattle leading to its surpassing Puget Sound on this score. By 2000, only 24% of Puget Sound residents lived in compact communities (neighborhoods with more than 12 people per acre) that can support public transit. In Greater Portland area, the number rose to 25%. This figure includes Clark County, Washington. If we consider only the Oregon Counties where growth management regulations are stricter, the number climbs to 28%. Once again, the metric suggests that Greater Vancouver was more effective at containing minimizing the development of land to accommodate the population growth of the 1990s than either Greater Portland or the Puget Sound region.

The impervious metric was the most technically demanding approach to implement due to the difficulty interpreting impervious surfaces with satellite images. On the one hand, a method that relies heavily on satellite imagery is attractive in a transboundary study area. Remotely sensed imagery provide a uniformly formatted data source that is unchanged across political jurisdictions. Further, because the entire study area lies within a reasonably uniform ecotone characterized by similar vegetation and precipitation patterns, the spectral signatures of various land classes used to classify impervious surfaces is consistent.

Unfortunately, impervious surfaces are a notoriously difficult landscape feature to measure with medium–coarse resolution remote sensing methods (Ji and Jensen, 1999). The image elements that comprise urban landscapes are highly heterogeneous. The spectral reflectance of materials in rooftops, parking lots, streets and sidewalks, all of which are impervious, may be dramatically different. This makes the selection of impervious endmembers for spectral mixture analysis difficult. SMA relies on a limited set of endmembers that contribute to the spectral composition of individual pixels. Therefore, it is possible to account for most of these elements in the mixture model. Nevertheless, some surfaces are easily confused with permeable materials such as cleared or bare earth. Roads are important contributors to total impervious areas but their narrow, linear nature is not always discernible within the resolution (30 m) of commonly utilized Thematic Mapper satellite imagery. In addition, detecting change in impervious surfaces is subject to many of the standard problems posed by remote sensing techniques: image calibration; topographic and atmospheric correction; annual variation in precipitation that affects the spectral signature of vegetated surfaces.

Typical verification techniques include comparing SMA results to the inverse of vegetation data derived from the same imagery using the NDVI (Ridd, 1995), comparison of SMA derived impervious fractions with on-the-ground measurements taken in sample locations (Mathias and Martin, 2003), or the co-registration of SMA results with higher resolution imagery such as ASTER or color-infrared photos which permit statistical comparison that accounts for signal noise and registration error (Ji and Jensen, 1999). Most studies find error rates differ with increasing levels of predicted imperviousness (Yang et al., 2003).

Results of this analysis are reported in wide ranges because of the difficulty distinguishing actual changes in composition at the pixel level with finer accuracy and because resources were unavailable to perform accuracy assessments with the degree of precision outlined in the studies cited here. Some basic comparisons were made by assessing the percentage of change in clusters of pixels coinciding to aerial photography taken at similar times. A delineation estimating impervious surfaces for each aerial was made by creating vector outlines in a GIS and the area of each vector was summed for each year and then subtracted to compute percent change. This was sufficient to provide confidence within the classification ranges reported on the maps included here.

For future updates at frequent intervals, considerable analytical effort is required to ensure that marginal increases in impervious surface from one year to another are accurately distinguished from other forms of land use change and from other sources of error.

7. Conclusions

Though the results confirm the value of varied approaches, it is clear that each metric reveals a different dimension of urban sprawl and is necessarily subject to various limitations. Table 4 summarizes each metric in the context of the challenges laid out in the introduction.

As a dynamic landscape form, the character and shape of urban sprawl is highly dependent upon the spatial and temporal scale at which it is studied. This study explains how, and to a lesser degree why, urban sprawl took different forms in three North American metropolitan centers subject to very similar socio-economic forces. Using three distinct analytical metrics, it also reveals the advantages and disadvantages to researching landscape form using varied methods that account for the effects of spatial and temporal scale. One frequent problem with many sprawl measurement techniques is an inability to recognize the landscape features of sprawl in low-density, rural lands where growth pressures may have their greatest impacts. The permit metric provided the resolution necessary to capture this phenomenon. It was also useful in disaggregating the patterns of growth within a metropolitan region to understand how public policy differences across a metropolitan region may influence development patterns.

Table 4
Comparison of each metric's performance against the evaluation criteria

Methods/evaluation criteria	Comparable data	Timescale and interval	Resolution/scale problems
Impervious metric	Consistent spectral signature across region; ignores international border	Classification error and noise in imagery analysis makes change analysis over small time intervals difficult	High resolution captures full heterogeneity of impervious surfaces, making classification and accuracy assessment difficult
Neighborhood metric	Population density metric easily calculated from data available in both countries	Census schedule varies, as does modeling of inter-decadal updates	Overcomes resolution issues with dasymetric methods and dynamically delineated, density-based neighborhoods instead of relying on census blocks/tracts
Permit metric	Locally collected data in variety of formats, various attributes, timescales, levels of reliability	High spatio-temporal resolution captures effects of policy changes	Provides a high spatial resolution if able to georeference and reconcile data from multiple jurisdictions

The flexibility of the neighborhood metric was also effective at quantifying rural land change. Rather than aggregating density data at the scale of census block groups or tracts, which must grow larger in space as population decreases, the approach dynamically defined the boundaries of sprawling neighborhoods by calculating changes in population density at the scale of 30 m pixels. Taking advantage of the additional spatial resolution provided by dasymetric mapping techniques, the result provided a more detailed, spatially explicit assessment of changes in density defined neighborhoods for the study period, revealing whether each metropolitan region was adding responding to population growth by expanding its high or low-density footprint. The approach also provided information that was useful in evaluating the findings of the permit metric in some areas where actual building permit data were unavailable.

This research provides results illustrating the implications and potential benefits of using multiple methods to evaluate complex landscape phenomena. Clearly no single methods proved superior with respect to all evaluation criteria. But by combining the results of multiple approaches the limitations imposed by spatial and temporal scale upon input data and the uncertainties inherent in complicated data analysis were mitigated.

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References

Adams, J.B., Smith, M.O., et al., 1986. Spectral mixture modeling: a new analysis of rock and soil types at the Viking Lander 1 site. J. Geophys. Res. 91 (B8), 8098–8112.

Adams, J.B., Smith, M.O., et al., 1989. Simple models for complex natural surfaces: a strategy for the hyperspectral era of remote sensing. Proc. IGARSS 1989 Vancouver, BC 1, 16–21.

Adams, J.B., Smith, M.O., et al., 1993. Imaging spectroscopy: interpretation based on spectral mixture analysis. In: Pieters, C.M., Englert, P. (Eds.), Remote Geochemical Analysis: Elemental and Mineralogical Composition, vol. 7. Cambridge University Press, New York, pp. 145–166.

Booth, D.B., 2000. Forest Cover, Impervious Surface Area and the Mitigation of Urbanization Impacts in King County. King County Water and Land Resources Division, Washington.

Booth, D.B., Jackson, C.R., 1997. Urbanization of aquatic systems: degradation thresholds, storm water detection and the limits of mitigation. J. Am. Water Resour. Assoc. 33 (5), 1077–1090.

Chin, N., 2002. Unearthing the roots of urban sprawl: a critical analysis of form, function and methodology. Working paper 47. Centre for Advanced Spatial Analysis. University College, London, http://www.casa.ucl.ac.uk/working_papers/Paper%2047.pdf.

Clapham Jr., W.B., 2003. Continuum-based classification of remotely sensed imagery to describe urban sprawl on a watershed scale. Remote Sens. Environ. 86, 322–340.

Daniels, T.L., 1998. The struggle to manage growth in the metropolitan fringe. In: McClendon, B., Pable, B. (Eds.), Proceedings of the 1998 National Planning Conference "Revolutionary Ideas in Planning", April 4–7, American Planning Association.

Durning, A., Williams-Derry, C., Chu, E., dePlace, E., 2002. This Place on Earth 2002: Measuring What Matters. .

El Nasser, H., Overberg, P., February 2001. A Comprehensive Look at Sprawl in America. USA Today, http://www.usatoday.com/news/ndsmon07.htm.

Ewing, R., 1994. Causes, characteristics, and effects of sprawl: a literature review. Environ. Urban Issues 21 (2), 1–15.

Fulton, W., Pendall, R., Nguyen, M., Harrison, A., 2001. Who Sprawls Most? How Growth Patterns Differ Across the U.S. Center on Urban & Metropolitan Policy. The Brookings Institution.

Gustafson, E.J., 1998. Quantifying landscape spatial pattern: what is the state of the art? Ecosystems 1, 143–156.

Handy, S.L., Niemeier, D.A., 1997. Measuring accessibility: an exploration of issues and alternatives. Environ. Plan. A29, 1175–1194.

Holloway, S.R., Schumaker, J., Redmond, R.L., 1997. People and Place: Dasymetric Mapping Using ARC/INFO. University of Montana, Missoula.

Imhoff, M.L., et al., 2000. The use of multisource satellite and geospatial data to study the effect or urbanization on primary productivity in the United States. IEEE Trans. Geosci. Remote Sens. 38 (6), 2549–2556.

Ji, M., Jensen, John R., December 1999. Effectiveness of Subpixel Analysis in Detecting and Quantifying Urban Imperviousness from Landsat Thematic Mapper Imagery, vol. 14. Geocarto International.

Kolankiewicz, L., Beck, R., 2001. Weighing Sprawl Factors in Large Cities: Analysis of U.S. Bureau of the Census Data on the 100 Largest Urbanized Areas of the United States, http://www.sprawlcity.org/studyUSA/index.html.

Lewis, M., March 2001. Census 2000: I-5 Corridor Drives Population Increase. The Seattle Post-Intelligencer, In: http://seattlepi.nwsource.com/local/grow272.shtml.

Mathias, B., Martin, H., 2003. Mapping imperviousness using NDVI and linear spectral unmixing of ASTER data in the Cologne–Bonn region (Germany). In: Proceedings of the SPIE 10th International Symposium on Remote Sensing, vol. 8012, September, Barcelona, Spain.

May, C.W., Horner, R., Karr, J.R., Mar, B.W., Welch, E.B., 2000. Effects of urbanization on small streams in the Puget Sound ecoregion. Watershed Protection Techniques 2 (4) 483–494. In: The Practice of Watershed Protection. Center for Watershed Protection.

Mazza, P., Fodor, E., 2000. Taking its Toll: The Hidden Costs of Sprawl in Washington State. Climate Solutions, In: http://www.climatesolutions.org/.

Newman, P.W.G., Kenworthy, J.R., 1989. Cities and Automobile Dependence. Gower Technical Press, Brookfield, VT.

Northwest Environment Watch, 2004. Cascadia Scorecard. Seven Trends Shaping the Northwest, In: http://www.northwestwatch.org.

Rickets, T., Imhoff, M., 2003. Biodiversity, urban areas, and agriculture: locating priority ecoregions for conservation. Conserv. Ecol. 8 (2), 1.

Ridd, M.K., 1995. Exploring a V–I–S (vegetation–impervious surfacesoil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities. Int. J. Remote Sens. 12, 2165–2185.

Sabol, D.E., Roberts, D.A., et al., 1993. Mapping and monitoring changes in vegetation communities of Jasper Ridge, CA using spectral fractions derived from AVIRIS images. In: Proceedings of the 4th Annual JPL Airborne Geoscience Workshop, Jet Propulsion Laboratory, Washington, DC.

Smith, M.O., Ustin, S.L., et al., 1990. Vegetation in deserts: I. A regional measure of abundance from multispectral images. Remote Sens. Environ. 3, 1–26.

Sudhira, H.S., Ramachandra, T.V., Jagadish, K.S., 2003. Urban sprawl: metrics, dynamics and modeling using GIS. Int. J. Appl. Earth Observ. Geoinform. V5, 29–39.

Sutton, P., 2003. A scale-adjusted measure of “urban sprawl” using nighttime satellite imagery. Remote Sens. Environ. 86, 353–369.

Theobald, D.M., 2001. Land-use dynamics beyond the American urban fringe. Geogr. Rev. 91 (3), 544.

Torrens, P.M, Alberti, M., 2000. Measuring sprawl. Working paper no. 27. Centre for Advanced Spatial Analysis, University College, London, http://www.casa.ucl.ac.uk/measuring_sprawl.pdf.

Ustin, S.L., Smith, M.O., et al., 1993. Remote Sensing of Ecological Processes: A Strategy for Developing and Testing Ecological Models Using Spectral Mixing Analysis. Scaling Physiological Processes: Leaf to Globe Academic Press, Inc., pp. 339–357.

Yang, L., Huang, C., Homer, C.G., Wylie, B.K., Coan, M.J., 2003. USGS Eros Data Center. Sioux Falls. South Dakota. Can. J. Remote Sens. 29 (2), 230–240.