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Urban growth patterns and growth management boundaries in the Central Puget Sound, Washington, 1986–2007

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Abstract Many regions of the globe are experiencing rapid urban growth, the location and intensity of which can have negative effects on ecological and social systems. In some locales, planners and policy makers have used urban growth boundaries to direct the location and intensity of development; however the empirical evidence for the efficacy of such policies is mixed. Monitoring the location of urban growth is an essential first step in understanding how the system has changed over time. In addition, if regulations purporting to direct urban growth to specific locales are present, it is important to evaluate if the desired pattern (or change in pattern) has been observed. In this paper, we document land cover and change across six dates (1986, 1991, 1995, 1999, 2002, and 2007) for six counties in the Central Puget Sound, Washington State, USA. We explore patterns of change by three different spatial partitions (the region, each county, 2000 U.S. Census Tracks), and with respect to urban growth boundaries implemented in the late 1990's as part of the state's Growth Management Act. Urban land cover increased from 8 to 19% of the study area between 1986 and 2007, while lowland deciduous and mixed forests decreased from 21 to 13% and grass and agriculture decreased from 11 to 8%. Land in urban classes outside of the urban growth boundaries increased more rapidly (by area and percentage of new urban land cover) than land within the urban growth boundaries, suggesting that the intended effect of the Growth Management Act to direct growth to within the urban growth boundaries may not have been accomplished by 2007. Urban sprawl, as estimated by the area of land per capita, increased overall within the

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region, with the more rural counties within commuting distance to cities having the highest rate of increase observed. Land cover data is increasingly available and can be used to rapidly evaluate urban development patterns over large areas. Such data are important inputs for policy makers, urban planners, and modelers alike to manage and plan for future population, land use, and land cover changes.

Keywords Land cover change · Spatial patterns · Urban growth · Urban growth boundary · Growth management · Urban-rural interface · Sprawl

Introduction

Urbanization, the conversion of lands that were previously undeveloped or in low density and low intensity forms of development (e.g., rural areas, agricultural lands) to urban land cover, is occurring at a rapid pace throughout the world (Houghton 1994) and the U.S. in particular (Brown et al. 2005). The land area that is urbanized continues to increase as the human population grows (Alberti et al. 2003; Grimm et al. 2000; Houghton 1994; Meyer and Turner 1992), with approximately 3% of Earth's land area currently in urban land cover (Imhoff et al. 2004). Urban growth and associated land use and land cover change have numerous effects on ecological and social systems (Foley et al. 2005). Urbanization changes and often substitutes natural ecosystem processes (i.e., surface water runoff, ground water recharge, nitrogen balances, light availability) with human constructed infrastructure (e.g., sewer systems and wastewater treatment plants).

Ecosystems are often degraded with urbanization. Documenting and monitoring land cover change over time is essential for understanding both system trends and the specific changes that have occurred (Ji et al. 2006). As areas become developed and land uses change from primarily production agriculture and forestry to residential, commercial, and industrial uses, the land cover of these areas change significantly both in species composition (e.g., from forest stands to non-native shrubs, lawn, and planted tree species with remnant patches of native forest) and in structure with more impervious surface area and simplified vertical diversity of vegetation (Robinson et al. 2005). The conversion of large areas of agricultural and forested lands, which hold great stores of biodiversity (Foley et al. 2005), into developed land cover has potential impact on the native biodiversity of an area (Hansen et al. 2001; Hepinstall et al. 2009; Pearson et al. 1999). Characterizing land cover of urban and urbanizing areas and change over time are important to several fields including urban ecology and urban planning (Alberti et al. 2003; Powell et al. 2008; Robinson et al. 2005; Yang et al. 2003), land cover change modeling (Hepinstall et al. 2008) and landscape ecology (Hobbs and Wu 2007).

Documenting patterns of urban development is also important to urban and regional planners who are interested in directing growth to be more efficient with the co-location of infrastructure and public services with residential areas thereby reducing transportation costs with concomitant reductions in greenhouse gas emissions. Land use regulations (e.g., zoning and building codes) can also be used to direct urbanization in ways that have fewer negative impacts on biological systems by, for example, slowing the conversion of productive agricultural lands or forests to development. Low-density, dispersed, and leap-frog development, often labeled "urban sprawl" (Kunstler 1994) at the edges of existing metropolitan areas or "rural sprawl" (Radeloff et al. 2005) in rural areas has been a common development pattern throughout the U.S. (Theobald 2001), Canada, Japan, and portions of Europe (Millward 2006).

One method for mitigating urban growth patterns that are perceived as negative (i.e., sprawl) is through planning and the institution of development boundaries such as urban growth boundaries (UGB) beyond which urban development is discouraged and within which planned growth is encouraged (Millward 2006). UGB are development boundaries with accompanying regulations set up by local municipalities designed to focus high-density urban development inside and conserve rural and undeveloped lands outside of the boundaries. The boundaries are specifically delineated to provide enough developable land to accommodate the projected growth in population for the region ~20 years into the future (Cho et al. 2008). Planned growth or "smart growth" includes many ideas including: mixed land uses with compact building design; walkable communities; and preservation of open space, agricultural lands, and critical environmental areas (Tregoning et al. 2002). Several studies have concluded that in theory, UGB would lead to economically efficient anti-sprawl solutions (Bento et al. 2006) and increase social welfare by managing growth and coordinating with infrastructure investment cycles (Ding et al. 1999).

These "strong control" planning techniques have been implemented in many locales including Portland, Oregon (Harvey and Works 2002), Vancouver, British Columbia (Tomalty 2002), and Washington State since sprawl was recognized as a potential problem in the U.S. in the early 1970's (Real Estate Research Corp 1974). Different levels of control of urban growth are available depending on the goals of the growth management legislation (Millward 2006), but generally there are areas where urban development is promoted with areas beyond these boundaries being designated as "open space" or a "green belt" of undeveloped lands.

The empirical evidence for UGB actually slowing sprawling development is mixed with studies indicating slowed growth (Gosnell et al. 2011; Kline 2005; Kline and Alig 1999; Nelson and Moore 1993), mixed results depending on location within urban or suburban areas (Cho et al. 2008), or negative "spillover" effects of pushing development across state borders (Jun and Hur 2001). Portland, Oregon was an early adopter of UGB in the U.S., passing legislation to direct the location of growth in 1973. In an evaluation of the number of residential building permits and land subdivisions between 1985 and 1989, it was clear the UGB were having the desired effect with over 90% of permits and 98.8% of subdivisions located within the UGB (Nelson and Moore 1993). Analysis of the effects of Portland's 1979 UGB, which was created primarily to contain urban growth and protect agricultural and forest lands from urban development, reveals that even with this strict boundary, many large-lot (low density) parcels were built for non-agricultural uses since the enforcement of the boundary in 1985 (Harvey and Works 2002) and often these occurred on the fringe of existing development, likely impeding future expansion of the UGB as populations continue to increase (Nelson and Moore 1993). Another study in Eastern Tennessee found that development was encouraged both within the UGB in already urban areas and outside of the UGB on the rural-urban margin (Cho et al. 2008).

It is possible to use geospatial data (i.e., land cover, land use, census data on population, housing density) to explore the spatial patterns of development. For example, Radeloff et al. (2005) explored the spatial pattern of housing growth across the U.S. from 1940 to 2000 using U.S. Census data and combined these data with a land cover map to determine both where housing growth at different densities occurred and how that related to the current extent of forests (i.e., potential stores of biodiversity). From this work the authors were able to document that increased housing density had occurred both along metropolitan fringes (urban sprawl) and in non-metropolitan areas (rural sprawl). However, this approach does not allow one to conclude why these patterns have occurred or to directly attribute them to land use planning efforts (Gosnell et al. 2011), but they do provide important information regarding observed change in land use/land cover.

Land cover maps derived from satellite-based remote sensing are increasingly available and provide a ready source of medium-resolution imagery (e.g., Landsat Thematic Mapper visible and infra-red sensors record data at 30-m resolution) from which to map land cover changes across time. Several recent studies have used remote sensing, land cover maps, and/or spatial pattern metrics to document temporal changes in urban extent and pattern (Boentje and Blinnikov 2007; Chen et al. 2000; Epstein et al. 2002; Herold et al. 2005; Ji et al. 2001; Lo and Yang 2002; Sudhira et al. 2004; Sutton 2003; Yang and Lo 2002; Yuan et al. 2005). Herold et al. (2003) provide a review of spatial metrics and methods used to measure urban land cover using remotely sensed imagery.

The objective of our study was to identify spatial patterns of land cover over time by different political jurisdictions and growth management policies. Specifically, we compared temporal changes in composition and configuration of land cover at three spatial scales: 1) a six county region in of the Central Puget Sound; 2) by individual counties; and 3) by census tracts. We also compared changes with respect to Urban Growth Boundaries designated as part of the 1990 Growth Management Act and implemented by counties and cities through comprehensive plans developed in the mid 1990s through the early 2000's. Finally, we compared land cover change with population estimates and calculated a per-capita consumption of land over time as one of many possible metrics describing sprawl.

Similar to Ji et al. (2006), we believe that it is important to conduct analyses at scales relevant to local and regional jurisdictions where decisions regarding planning and development options occur. At the regional level, the Puget Sound Regional Council is a regional planning agency (and designated Metropolitan Planning Organization for the region) currently composed of representatives from four counties (King, Kitsap, Pierce, and Snohomish) and cities, towns, ports, tribes, transit agencies, and the state government. While not generally a spatial unit used in planning, we conducted analysis for each census track as our finest resolution analysis primarily to develop a digital database that will be useful to other researchers since there is a wealth of information resulting from U.S. Censuses. We were specifically interested in how land cover patterns changed over time and space and whether there were any discernible patterns that could be attributed to urban growth boundaries implemented in the late 1990's and early 2000's.

Evaluating the effectiveness of UGB is difficult since myriad processes are present in an urban and urbanizing region and it is difficult to attribute any one observed pattern to a specific policy. However, in theory, if designated UGB provide adequate buildable land and focus new growth within their boundaries, then several hypotheses can be postulated concerning the location and intensity of new growth: 1) greater development by area and by percentage of new development observed in one time period will have occurred within the boundaries; and 2) discrete patches of new development in each time period will be larger inside rather than outside of the UGB. While we do not attempt to directly evaluate the effectiveness of the UGB at directing new urban development, these hypotheses concerning the location and configuration of new development can be tested using increasingly available land use and land cover (LULC) data. Landsat Thematic Mapper satellite imagery which can be processed into land cover maps is now freely available, likely stimulating the production of additional LULC maps.

Study area

The study area is approximately 17,700 km^2 of land area encompassing the Central Puget Sound of western Washington, USA, (Fig. 1) and includes all or portions of six counties

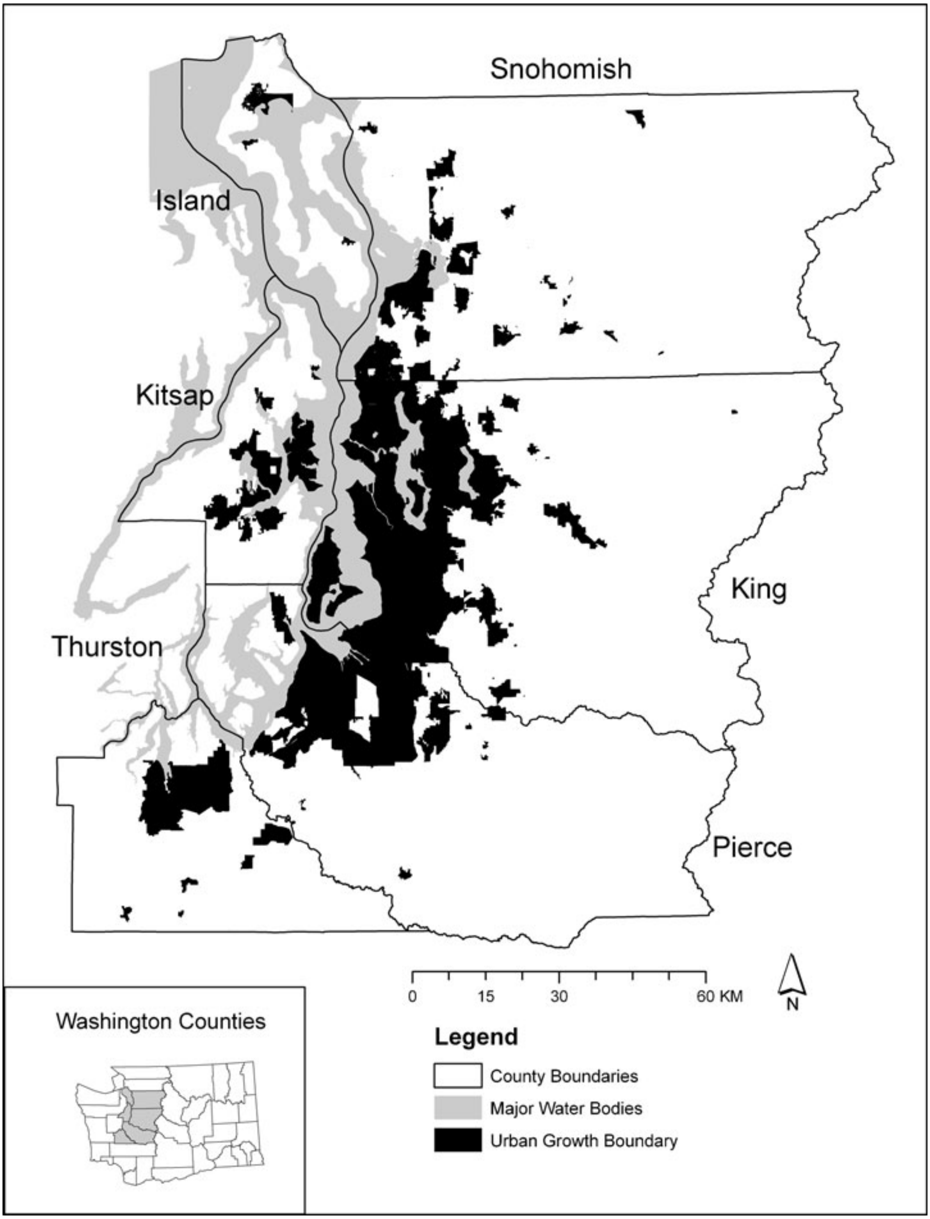

Fig. 1 Six county study area in western Washington, USA showing county boundaries and the 2002 Urban Growth Boundaries

(Island, King, Kitsap, Pierce, Snohomish, and Thurston) and the major metropolitan areas of Seattle, Tacoma, Bellevue, and Everett. The northwestern U.S. has experienced regionally high levels of population growth, especially during the last 30 years. Specifically, the six counties in our study area have experienced an average growth rate of 4.2% per year from 1986 to 2007; and is projected to grow by 31% (an additional 1 million people from 2000) by 2025 (Office of Financial Management, State of Washington: http://www.ofm.wa.gov/pop/ accessed 16 May 2010).

In 1990 the state of Washington legislature passed the "Growth Management Act" (GMA; "Growth management–planning by selected counties and cities", RCW 36.70A), which mandated the use of comprehensive land use planning with the goal of preventing unplanned and haphazard land development—the type of growth that typically results in dispersed development patterns and highly fragmented exurban development and is often labeled as sprawl or urban sprawl. Counties of a certain size and growth rate (>50,000 inhabitants with >10% in previous 10 years or counties with any population size and >20% growth rate) and the cities within them are required to develop comprehensive plans and development regulations guided by 14 goals covering various social, economic, and environmental elements. Section 36.70A.110 sets forth the designation of urban growth areas in comprehensive plans by setting boundaries within which growth is encouraged and outside of which growth "can only occur if it is not urban in nature". The Act does not explicitly define "not urban in nature", but it can be understood as single-family residential on lots larger than ~0.5 acres. By October 1, 1993, the counties that met the growth criteria requiring them to follow RCW 36.70A were expected to have provisional urban growth areas designated. Four of the six counties in our study area (King, Kitsap, Pierce, and Snohomish) began in 1993 to develop comprehensive plans in compliance with the GMA. By 1994 King County had adopted a comprehensive plan that designated urban growth areas and the four counties had formed the Puget Sound Regional Council through which the VISION 2020 document was developed that outlined regional planning policies that were in compliance with the GMA. Pierce, Thurston, and Snohomish Counties followed with comprehensive plans enacted in 1995; Kitsap and Island Counties in 1998.

The GMA uses state funding of public works to encourage jurisdictional compliance, stating that, "only those jurisdictions in compliance with the review and revision schedules of the growth management act are eligible to receive funds from the public works assistance and water quality accounts in the state treasury" (36.70A.130 Notes: Intent 2005c294). However, many jurisdictions did not comply with original and subsequently revised deadlines, so that by 2005 the act was amended to allow jurisdictions making significant progress towards compliance to be granted an additional 12 months of eligibility for funds (36.70A.130 Notes: Intent 2005c294). Because of the difficulty in determining the exact growth management boundaries for each jurisdiction and when each was enacted and enforced, we used a spatial database containing GMA boundaries available statewide with an effective date of 2002 when making comparisons of growth inside and outside of designated urban growth boundaries.

Methods

Land cover data

We used 14-class land cover data for 1986, 1991, 1995, 1999, 2002, and 2007 developed from a combination of Landsat Thematic Mapper (TM) and Enhanced TM (ETM+) imagery (Hepinstall-Cymerman et al. 2009). Multiple methods were used to differentiate 14 land cover classes in each image. Supervised and unsupervised classifications were combined with spectral unmixing techniques on multi-season imagery for each date. Differences between leaf-on (June-July) and leaf-off images (March–April) were used to differentiate between land cover classes spectrally similar in one season and dissimilar in another (e.g., deciduous versus coniferous forest, agriculture versus low-density urban). Multi-season data has been successfully used in the past (Lunetta and Balogh 1999; Oetter et al. 2001) to differentiate land cover classes that may be spectrally similar in one season and dissimilar in another. In addition, the surface heterogeneity of urban areas leads to spectrally heterogeneous imagery at small spatial scales. Spectral unmixing of the leaf-on imagery was used to separate heavy urban (80–100% impervious area), medium urban (50–80% impervious), and light urban (20–50% impervious). The level of impervious area is an important determinant of many ecosystem processes (Lu and Weng 2006; Tang et al. 2005). Landscape trajectories, or temporal patterns of land cover change, were used to correct for classification errors between dates so that urban areas either stayed at the same level of imperviousness or became more impervious over time. Several land cover classes were derived from ancillary GIS layers (open water, non-forested wetland, shorelines, and ice/snow fields); we did not consider these classes in this study since they are constant throughout the land cover maps.

Comparing land cover composition and configuration over time and space

Land cover maps for each date were compared pixel-by-pixel to determine land cover change during our study period (1986–2007). We calculated landscape composition (area and percentage) and patch-based landscape composition metrics for three spatial strata: 1) the six county study area; 2) for each county by date; and 3) by U.S. census tract (2000) boundaries. We also calculated change between subsequent dates for each spatial stratum. Additionally, we calculated the same metrics separately for those areas inside (i.e., urban growth areas) and outside of the 2002 UGB (obtained from the State of Washington Department of Ecology) for each date and stratum. We calculated the area and percentage of new urban (pixels that were not an urban class in the previous time period but subsequently became urban) for 1991–2007. We used Fragstats 3.3 (McGarigal et al. 2002) to calculate patch-based "landscape metrics" or more broadly "spatial metrics" (Herold et al. 2003) measuring landscape configuration for all urban classes combined (Heavy, Medium, Light, Cleared for Development; Table 1). We selected metrics based on previous studies (Alberti et al. 2007; Hepinstall et al. 2008, 2009; Herold et al. 2003; Ji et al. 2006) and included

Table 1 Land cover classes used in this study

Final classification	Abbreviation	Class definition
Heavy intensity urban	HIU	>80% Impervious Area
Medium intensity urban	MIU	50–80% Impervious Area
Light intensity urban & land cleared for development	LIU	20–50% Impervious Area class combined with Land that was vegetated in a previous time step and urban in a later time step
Grass	GR	Developed Grass and Grasslands
Agriculture	AG	Row Crops, Pastures
Deciduous and mixed forest	DMF	>80% Deciduous Trees, 10–80% each Decid./Conif. Trees
Coniferous forest	CF	>80% Coniferous Trees
Clearcut forest & regenerating forest	CC & REG	Clearcut Forest and Re-growing Forest combined
Other	Other	Water, Non-forested Wetlands, Shoreline (tidal areas bare during low tide), and Snow/Ice/Bare Rock (high elevation areas with no vegetation or snow cover) combined

metrics that measure the amount of edge, the shape of patches, and aggregation of patches. Specifically, we calculated the following metrics for individual classes: number of patches per unit area (PD) using 8-way neighbors to define patches; the amount of edge per unit area (ED); shape of patches (LSI); and aggregation index (AI) which measures how often pixels are contiguous to pixels of the same class scaled from 1 to 100 (McGarigal et al. 2002). In addition to the class-based landscape metrics, we calculated two metrics that measured patterns across all 14 land cover classes at once (i.e., "landscape metrics" in Fragstats) as an indication landscape patterns integrating all mapped classes: Shannon's Diversity Index (SHDI) which measures the number of different land cover classes present; and Shannon's Evenness Index (SHEI) which measures how evenly distributed (by area) the existing land cover classes are across the study area. In urbanizing rural or forested landscapes, SHDI will increase and SHEI will decrease; urbanizing suburban landscapes will experience the opposite trend.

Measures of urban sprawl

To understand how increased urban land cover tracked with population (e.g., per capita land consumption), we calculated an annualized urban sprawl index (AUSI) as the area (km^2) of new urban land cover divided by the population change (in thousands) for the same time period (person per 0.10 ha), each annualized by the number of years represented. While there are many different measures of "sprawl" available, most require fine-scaled data on specific landscape elements (e.g., number of cul-de-sacs, sidewalks) that were not available for our study area. Our AUSI metric is similar to the urban sprawl index in Yuan et al. (2005) where we have annualized change to be able to compare across multiple time periods. Population data by county were downloaded from the Washington State Office of Financial Management (http://www.ofm.wa.gov/pop accessed on 4 July 2007 and 16 May 2010) and represent yearly estimates of the number of residents in each county.

Results

Land cover composition

Between 1986 and 2007 urban areas spread out from the existing urban core cities of Seattle, Bellevue, Tacoma, Olympia, Everett, and Bremerton, into the lower elevations and up canyons. The area of land in urban classes has steadily increased at the same time that grass, agriculture, and forested classes were decreasing (Table 2). Urban areas were primarily converted from grass, agriculture, and deciduous and mixed forest. Some of these patterns are driven by changes in the yearly extent of snow when the images were acquired and problems with classifying high elevation conifer that still had snow on the ground. For example, the large differences between 2007 and 2002 in grass and coniferous forest are driven primarily by differences at high elevations and are likely due to discrepancy in the land cover maps rather than actual land cover changes on the ground (not shown).

When comparing the total area of each class across time within and outside of the UGB we observed that urban land cover increased from 1,167 km^2 in 1986 to 1,936 km^2 in 2007 inside of the UGB, an increase of 65.9%, and representing 41.3% and 68.6% of the area inside the UGB (Table 2). Conversely, urban areas outside of the UGB, while covering less

Table 2 Total area (km^2) for each land cover class Inside or Outside of 2002 urban growth boundaries and percent inside (%IN), Total Urban (HIU, MIU and LIU combined; km^2), Total percent of Zone (inside or outside of UGB) in Urban, and % of Total Urban Inside or Outside of UGB

		HIU	MIU	LIU	GR	AG	DMF	CF	CC&REG	Other	Total	Total urban	% of zone urban	% of total urban
1986	Inside	229.8	553.3	383.6	431.9	56.6	575.6	387.7	44.6	159.8	2822.9	1166.7	41.3	71.5
	Outside	22.6	90.7	351.6	1322.1	518.9	3650.2	6518.3	1244.2	3820.5	17539.0	464.9	2.7	28.5
	Total	252.4	644.0	735.2	1754.0	575.5	4225.7	6906.0	1288.8	3980.3	20361.9	1631.6		
	%IN	91.1	85.9	52.2	24.6	9.8	13.6	5.6	3.5	4.0	13.9	71.5		
1991	Inside	287.4	712.9	458.7	317.7	92.1	498.6	270.4	25.8	159.2	2822.9	1459.0	51.7	62.1
	Outside	33.9	179.6	677.9	1358.3	699.1	3282.2	5757.5	1126.0	4424.7	17539.0	891.4	5.1	37.9
	Total	321.3	892.5	1136.6	1676.0	791.2	3780.8	6027.9	1151.8	4583.8	20361.9	2350.3		
	%IN	89.4	79.9	40.4	19.0	11.6	13.2	4.5	2.2	3.5	13.9	62.1		
1995	Inside	341.2	824.7	469.2	301.6	40.2	454.6	206.0	28.9	156.4	2822.9	1635.1	57.9	59.0
	Outside	44.3	270.5	823.3	1568.2	494.0	3353.6	5258.4	1404.7	4322.0	17539.0	1138.1	6.5	41.0
	Total	385.5	1095.2	1292.5	1869.8	534.2	3808.3	5464.5	1433.6	4478.4	20361.9	2773.2		
	%IN	88.5	75.3	36.3	16.1	7.5	11.9	3.8	2.0	3.5	13.9	59.0		
1999	Inside	422.0	836.9	488.6	244.1	39.6	399.1	205.1	31.2	156.1	2822.8	1747.6	61.9	55.9
	Outside	69.1	327.4	982.6	1279.4	438.1	2725.3	5349.3	1620.4	4483.0	17274.8	1379.2	8.0	44.1
	Total	491.2	1164.4	1471.3	1523.5	477.8	3124.4	5554.4	1651.6	4639.1	20097.6	3126.8		
	%IN	85.9	71.9	33.2	16.0	8.3	12.8	3.7	1.9	3.4	14.0	55.9		
2002	Inside	535.4	857.8	490.6	144.7	31.0	348.3	206.7	51.2	157.0	2822.8	1883.8	66.7	51.6
	Outside	103.2	441.2	1223.4	979.9	353.6	2554.0	5468.9	2253.9	3896.7	17274.8	1767.7	10.2	48.4
	Total	638.6	1299.0	1714.0	1124.6	384.6	2902.4	5675.6	2305.2	4053.7	20097.6	3651.6		
	%IN	83.8	66.0	28.6	12.9	8.1	12.0	3.6	2.2	3.9	14.0	51.6		
2007	Inside	575.7	920.9	439.4	151.6	44.4	317.2	176.2	38.1	159.3	2822.8	1935.9	68.6	51.7
	Outside	145.1	482.8	1180.8	1101.6	433.3	2306.8	4943.8	2640.4	4010.8	17245.4	1808.7	10.5	48.3
	Total	720.8	1403.7	1620.2	1253.2	477.7	2624.0	5120.0	2678.5	4170.1	20068.2	3744.6		
	%IN	79.9	65.6	27.1	12.1	9.3	12.1	3.4	1.4	3.8	14.1	51.7		

[1] Class abbreviations listed in Table 1

area in 1986 (465 km^2) increased 289% by 2007 to 1,809 km^2 (from 2.7% to 10.5% of the zone including unbuildable lands in the Cascade Mountains). Between 1986 and 2002 inside the UGB, heavy and medium intensity urban classes increased (151% and 66%, respectively) more than light intensity urban (15%). Outside of the UGB the pattern was similar but the percentage change was much larger (HIU: 542%; MIU 432%; LIU 236% increase). The percentage of each urban class that was inside the UGB steadily decreased at the same time the total area of urban land was increasing across the region; by 2007 the combined area for all urban classes for our study area indicated the nearly 50% of all urban land was located outside of the UGB. The increase in urban land cover came at the expense of Grass, Deciduous and Mixed Forest, and Coniferous Forest which all decreased in total area and in the percentage within the UGB.

Because the Growth Management Act was passed in the early 1990's, but not implemented until after 1995 or 1998, depending on the county in our study area, we compared annualized rates of increase in urban land cover across time to see if we could detect any patterns potentially attributable to the passage of comprehensive plans by each jurisdiction. More land area was being converted to urban classes outside of the UGB than inside the UGB across all dates with the greatest disparity in development occurring between 1999 and 2002 when we observed almost three times as much new urban land outside the UGB as inside (Fig. 2). The annualized rates (Fig. 2 numbers within bars) show a large increase in both the total amount of new urban and the amount occurring outside of the UGB between 1999 and 2002.

Visualizing the patterns of change in urban land cover with respect to the UGB is difficult given our large study area, the fine grain data, and the highly heterogeneous landscape. To highlight changes, we selected only those areas that changed into an urban class from a non-urban class in the previous date and then compared the distribution of these areas of new urban inside and outside of the UGB. New urban areas were predominately outside of the UGB, with 2002 representing the lowest percentage of new development occurring within the UGB; even while the amount of new urban increased substantially from the 1995 to 1999 time period (Fig. 2). We have included a figure mapping the patterns of new urban in 1999, 2002, and 2007 with respect to existing urban as of 1995 and the UGB for a small but representative section of King and Snohomish counties including northern Seattle and Bellevue (Fig. 3). While a large portion of the

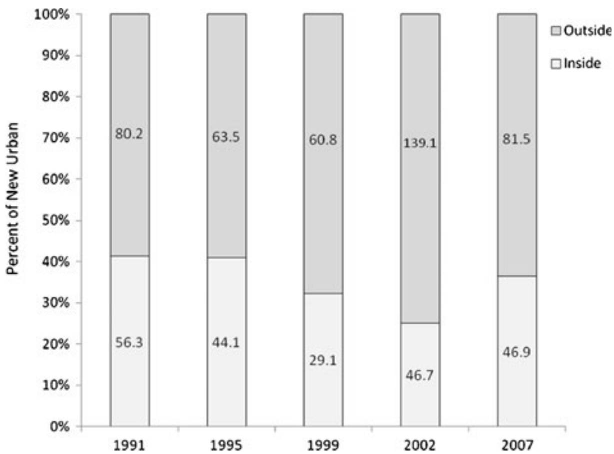

Fig. 2 New urban land cover distribution (% of total new urban since last date of land cover) inside or outside of 2002 Urban Growth Boundaries by year. *Numbers in bars* indicate the annualized area (km^2) of new urban added inside or outside of the UGB since the previous date

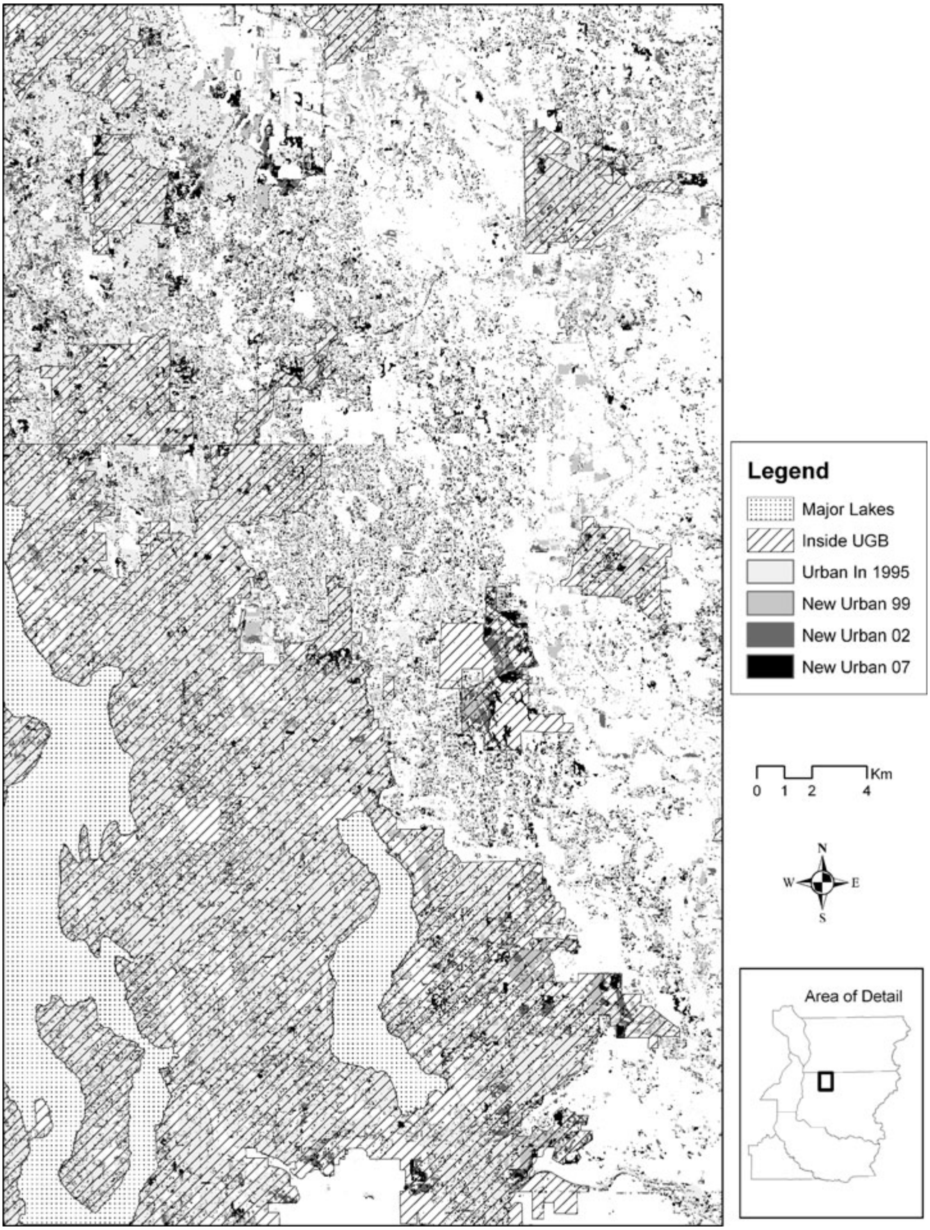

Fig. 3 Map of urban land cover in 1995 and new urban land cover in 1999, 2002, and 2007 in relation to the 2002 Urban Growth Boundary for a section of King and Snohomish counties showing the prevalence of new urban land cover outside of designated growth areas

section show was within the UGB and already urban in 1995, many new large patches of urban appear both inside and outside of the UGBs in each of the subsequent time periods. Additionally, many smaller areas of urban growth are present throughout the region as isolated patches or as expansions on existing developed areas; however, more of these small patches appear outside of the UGB.

We determined the temporal pattern of urban land cover (all urban classes combined) and new urban (areas that were not urban in the previous time step) inside and outside of the UGB by county (Fig. 4). All counties show a similar pattern with an increasing percentage of urban land cover occurring outside of the UGB until 2002 and a leveling off or slight decrease in this percentage between 2002 and 2007. King and Pierce, the more urban counties, have the majority of urban land cover within a UGB. Other more rural counties, especially Island County, have a small and steadily decreasing proportion of urban land cover in the county within their UGB. When looking at the location of new urban each time step, all counties except Pierce had substantially more of the new urban development occurring outside of the UGB than within. Even in King County, the county with the highest percentage of urban land, the proportion of new urban occurring within the UGB was low (~20%), with a noticeable dip in 2002.

To allow finer resolution of temporal changes in land cover, we measured changes occurring within each census track inside our study area. We calculated the percent change in urban area from 1986 to 2007 normalized by census track area to correct for the large disparity in track sizes (Fig. 5). Urban centers (e.g., Seattle, Bellevue, Tacoma, and Olympia) did not exhibit large changes as these areas were already developed in 1986. As expected, tracks of undeveloped lands ringing urban areas exhibited larger changes, with several increasing the areal extent of urban by up to 140%.

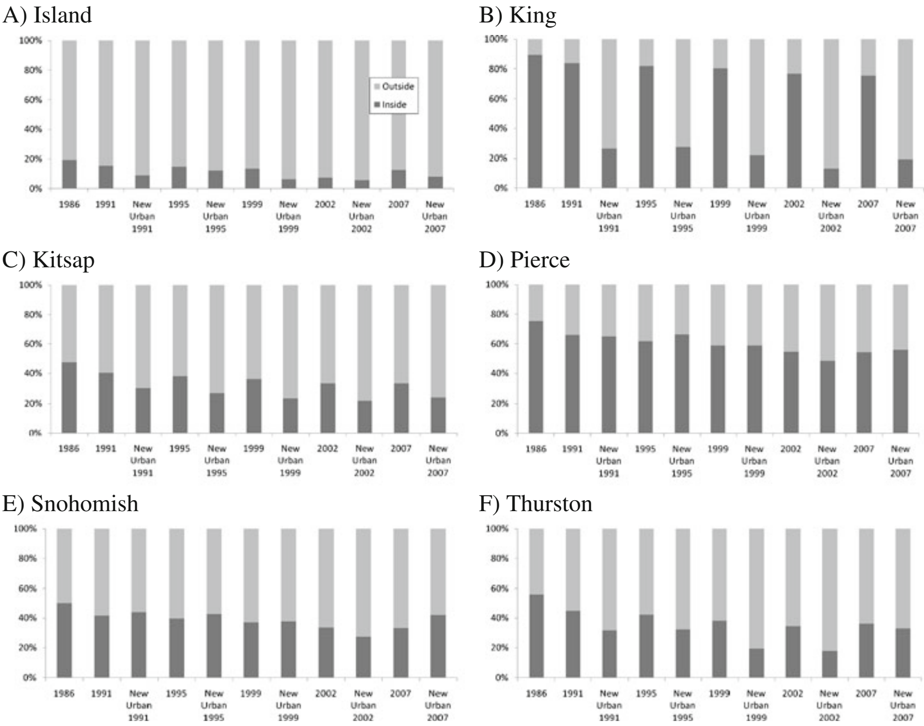

Fig. 4 County specific distribution of urban land cover and new urban for each date for all urban classes combined inside or outside of 2002 Urban Growth Boundaries by year

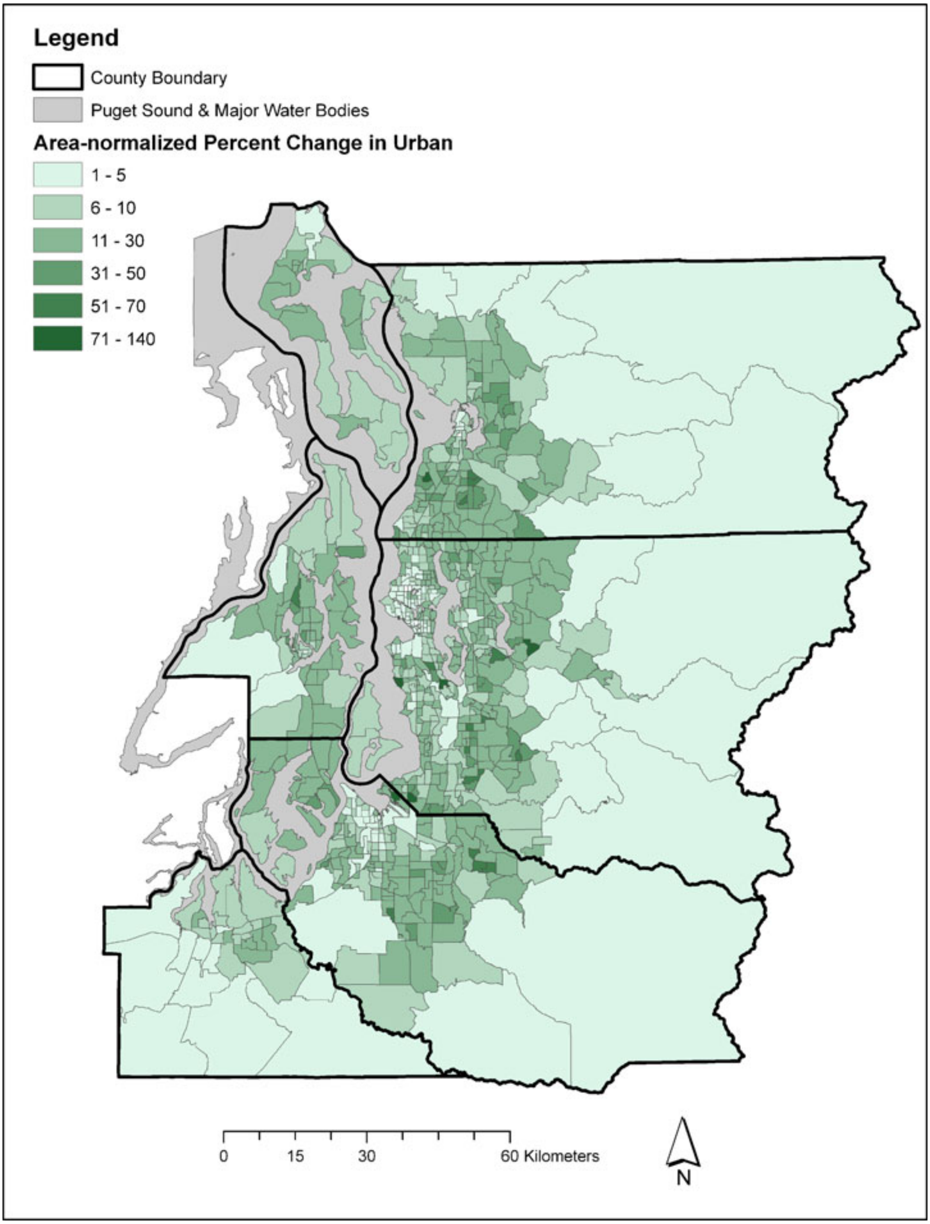

Fig. 5 Map of change in urban amount in each census track from 1986 to 2007 normalized by census track area

Land cover configuration

A previous study looked at changes in the patterns of landscape composition and configuration for this region from 1986 to 2002 using simple landscape metrics (Hepinstall-Cymerman et al. 2009). We extended this by including 2007 data and looking at more metrics over different politically defined spatial partitions (county and census track). Here we focus on six metrics calculated for all urban classes combined. Within in the UGB from 1986 to 2007, as the area of urban classes (CA) increased across all time periods (Table 2), LSI, ED, PD were decreasing and AI was increasing—all trends indicating that the overall pattern of urban growth was expansion of established urban areas and infill rather than the establishment of new patches of urban land cover (Fig. 6a). Outside of the UGB the patterns were more variable. Both PD and LSI generally peaked in 1991, and AI steadily increased from 1986 to 2007, indicating that the urban areas in this region were beginning to consolidate into larger patches (Fig. 6b). Edge Density, however, was increasing for all counties from 1986 to 2007 outside the UGB indicating that new urban areas were not always simply expansion.

The overall composition and configuration of the landscape clearly changed during the study period. Inside of the UGB, both the SHEI and SHDI decrease across all time periods indicating that the area inside the UGB was becoming less diverse and less even (Fig. 7). This trend matches the increase in urban area and elimination of patches of non-urban classes depicted by county in Fig. 6a. Outside of the UGB the trend is the reverse with a steady increase in both SHEI and SHDI over time, indicating both an increase in fragmentation (increased evenness indicates more even distribution of patch types) and an increase in diversity of class types as urban classes expanded into previously undeveloped areas.

Per-capita land consumption

We compared how changes in human population have tracked changes in urban land area (Table 3). Populations increased consistently (yearly range: 800 for Island County between 2002 and 2007 to 34,800 in King County between 1986 and 1991) across the six counties in our study area. The area in urban land cover increased yearly and relatively consistently for each county until the final time interval when the amount of change dropped significantly across all counties. Our basic annualized urban sprawl index (AUSI) indicated that new urban land cover was not clearly aligned with increased population across time or space. Specifically, King, Pierce, and Snohomish counties show the highest AUSI between (1999 and 2002), and the lowest AUSI levels observed in the final time period (2002–2007).

Discussion

This six county region underwent a large increase in urban land between 1986 and 2007, at the expense of grass, agriculture, and lowland deciduous and mixed forest. As the area of urban land cover grew, it became more consolidated and continuous within urban growth areas, while at the same time continuing to increase in area and number of discrete patches of new urban land cover outside of the urban growth areas. Similar patterns have been observed in other studies examining temporal changes in urban patterns (Ji et al. 2006; Torrens 2008)

Consistently across all dates, the percentage of new urban land that fell outside of the UGB was larger than the percentage of new urban land that fell within the UGB. The only exception was for Pierce County where the majority of land cover change to urban was occurring within the UGB for the county. Similarly, Carlson and Dierwechter (2007) found that the percentage of building permits in Pierce County that were located outside the UGB between 1991 and 2002 decreased from a high of 50% in 1993 to 23% by 2002 and attributed the change to the implementation of growth management beginning in 1995. Interestingly, between 1995 and 2007, the annual increase in urban area within the UGB

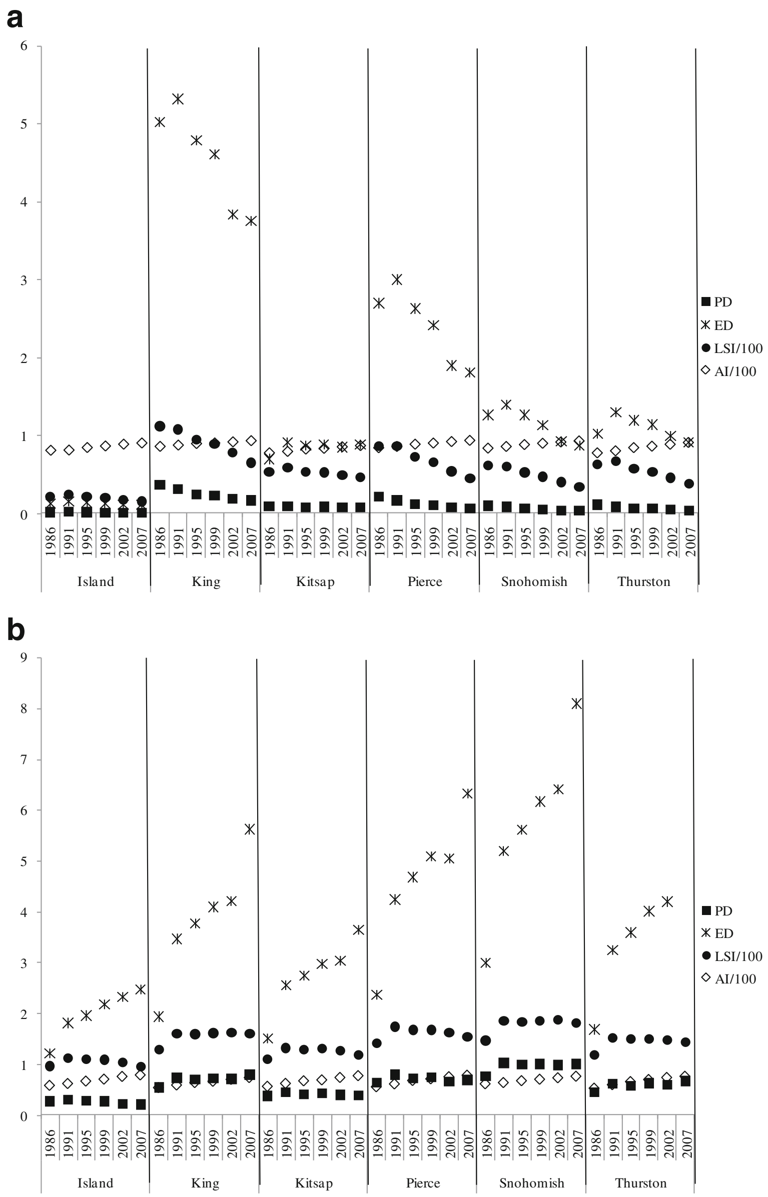

Fig. 6 Changes in four land cover configuration metrics (number of patches per 100 ha [PD]; meters of edge per hectare [ED]; landscape shape index [LSI]; number of like adjacencies—aggregation index [AI]) over time for all urban classes combined for: **a** areas inside the 2002 Urban Growth Boundary for each county; **b** areas outside the 2002 Urban Growth Boundary for each county. (LSI and AI are divided by 100 to allow presentation of all four metrics on the same scale)

held relatively steady, whereas the annual area converting to urban outside of the UGB peaked in the time period between 1999 and 2002. While each of the six counties in our study area all had GMA-compliant comprehensive plans by 1995 or 1998, it may be that these plans were not yet fully implemented or that building permits had been issued before

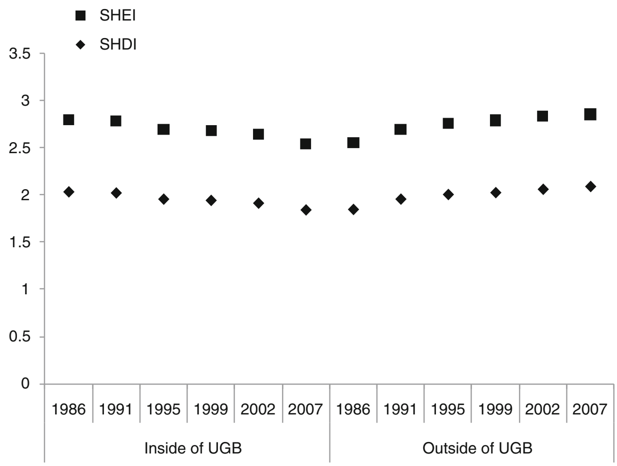

Fig. 7 Shannon evenness index (SHEI) and Shannon diversity index (SHDI) for the original 14-class land cover maps for areas inside (In) and outside (Out) of the 2002 Urban Growth Boundaries

the comprehensive plans went into effect. It is possible that the immediate response to the growth management policy may have been to increase the demand for land before the comprehensive plans were fully implemented for each municipality or region and growth management boundaries were being enforced. By 2007, it appears that the trend of an increasing percentage of urban land cover being located outside of designated urban growth areas was decreasing; however, region-wide new urban development was still occurring on nearly three times the land area outside of these designated growth areas than inside of them. The patterns of urban land cover outside of the UGB also suggests an increase in urban-non-urban edges over the past 20 years; interfaces that are detrimental for many ecological processes.

The observed increased rate of development of land outside urban growth areas prior to 2002 may be an attempt by land developers to accelerate development in areas that were likely to be "undevelopable" due to their location with respect to potential urban growth boundaries. Conversely, the increased rate of development outside of the UGB prior to their delineation may represent developers attempting to set a precedent for more liberal UGB boundaries. A much finer-scale analysis would be required to understand the cause and effect behind the observed patterns. Our results clearly show that areas outside of the UGB were being developed at rates higher than areas within the UGB and higher than would be expected if the UGB was enforced by each jurisdiction. Since the GMA was designed to limit growth outside of UGB to that "not urban in nature", it seems clear that the GMA has not been effective. It is important to note that given the spatial and class resolution of land cover data derived from Landsat Thematic Mapper imagery, there will be errors in our analyses attributable to errors in each land cover map. While we did not attempt to measure how errors may affect our results, we minimized errors in individual land cover maps by using grouped land cover classes rather than the full class resolution of the land cover data.

There are many different ways to conceptualize sprawl (Torrens 2008) and many more to measure the patterns of development and relate these measurements to the concept of sprawl (Bhatta et al. 2010a; Torrens 2008). The pattern of per-capita land consumption was one where the highest value observed for each county was during the time period after the passage but before the implementation of the Growth Management Act (1999–2002) with a decrease to the lowest levels observed in the final time period (2002–2007). While this

Table 3 Human population (in thousands) and annualized change in thousands (Δ pop / year), urban land cover area (km^2) and annualized change (Δ km^2/year) between dates, and an annualized urban sprawl index (annual urban area expansion / annual population expansion) for each county within the study area

Population (000)

	1986	1991	Δ pop/year	1995	Δ pop/year	1999	Δ pop/year	2002	Δ pop/year	2007	Δ pop/year
Island	51	62	2.2	66	1.1	71	1.1	73	0.8	78	1.1
King	1,376	1,550	34.8	1,625	18.8	1,712	21.7	1,774	20.7	1,861	17.4
Kitsap	167	197	5.9	218	5.3	230	2.8	235	1.7	245	2.0
Pierce	536	598	12.4	649	12.8	689	9.9	725	12.0	791	13.1
Snohomish	393	488	19.0	532	10.9	589	14.4	628	12.9	686	11.7
Thurston	143	168	4.9	186	4.7	203	4.2	212	3.0	238	5.1

Urban land cover (km^2)

	1986	1991	Δ km^2/year	1995	Δ km^2/year	1999	Δ km^2/year	2002	Δ km^2/year	2007	Δ km^2/year
Island	61.1	93.9	6.6	116.7	5.7	143.1	6.6	189.2	15.4	170.3	MD[1]
King	679.6	874.2	38.9	979.9	26.4	1055.9	19.0	1171.2	38.4	1226.0	10.9
Kitsap	111.8	188.6	15.4	228.8	10.1	258.6	7.5	323.4	21.6	329.1	1.1
Pierce	379.8	540.7	32.2	656.3	28.9	744.4	22.0	861.5	39.0	891.4	6.0
Snohomish	267.5	413.2	29.2	486.9	18.4	565.0	19.5	672.4	35.8	685.9	2.7
Thurston	131.9	238.9	21.4	300.3	15.4	361.2	15.2	439.7	26.2	442.0	0.4

Annualized urban sprawl index

	86–91	91–95	95–99	99–02	02–07
Island	2.9	5.4	6.2	18.6	MD[1]
King	1.1	1.4	0.9	1.9	0.6
Kitsap	2.6	1.9	2.6	12.6	0.6
Pierce	2.6	2.3	2.2	3.2	0.5
Snohomish	1.5	1.7	1.4	2.8	0.2
Thurston	4.4	3.3	3.6	8.6	0.1

[1] MD—data from northern Island County is missing from the 2007 land cover map precluding comparisons

pattern is likely due to many different economic drivers including the housing boom of the late 1990's and early 2000's followed by the housing slowdown starting in late 2006, this pattern may indicate a lower per capita land consumption due to the policies put in place with the GMA and comprehensive planning.

In addition, the two rural counties (Island and Kitsap) within commuting distance to the region's large urban areas, had large increases in AUSI and the highest AUSI value observed between 1999 and 2002, suggesting large amounts of dispersed development occurred during this time period in these two counties. Our AUSI values were much higher than those observed between 1986 and 2002 in the Minneapolis-St Paul metropolitan area (Yuan et al. 2005), suggesting that Central Puget Sound growth was more dispersed in form.

Our measure of sprawl is a simple metric that does not differentiate between cause and effect. For example, the available population data do not differentiate between single family households and multi-family units, nor do the urban land cover classes in our maps only portray pixels of residential development. Others have warned against using population as the sole indicator or urban development (Carlson and Dierwechter 2007; Ji et al. 2006) and we acknowledge that our results represent one way of evaluating sprawl in the aggregate. Our results could be improved by using building permits or the number of residential units or commercial square footage built each year or by calculating some of the more sophisticated metrics in the literature (Bhatta et al. 2010b; Torrens 2008). Such data have been used to model past and predict future urban development using UrbanSim (Waddell 2002), land cover change using the Land Cover Change Model (Hepinstall et al. 2008), and future avian diversity (Hepinstall et al. 2009).

Our land cover data for 2007 showed only a small increase in the urban land cover over 2002 levels. While it is likely that this reflects a decrease in housing starts and commercial development, it is also possible that since 2007 is the last time point in our map series, there was a slight under-classification of urban areas (although the reported accuracy was comparable for all years), leading to incorrect AUSI numbers and conclusions regarding the efficacy of Growth Management Act's Urban Growth Boundaries. Another possible source of error in our calculations was our use of the 2002 UGB spatial data since specific boundary locations were different both before and after that date. Reconstructing year-specific UGB, especially given the highly variable lag time between the application for a building permit and start or end of building related to that permit, may not allow a more precise calculation of AUSI or other sprawl metrics.

Conclusions

Monitoring changes in land cover across space and time is important to providing baseline data for a region. In the Central Puget Sound urban land cover has increased dramatically between 1986 and 2007, most often at the expense of forestlands. In addition, areas in grass and agricultural have declined in extent. Urban development has increased in areas where growth management regulations were expected to limit new development. Specifically, more new development occurred outside of the urban growth boundaries than within during our last time period (2002–2007), a pattern counter to what would be observed if the growth management policy had been effective in directing the location of new development. The observed changes have profound economic and ecological implications such as reduced habitat and resulting loss of avian diversity for native forest species (Donnelly and Marzluff 2006; Hepinstall et al. 2008; Marzluff 2005; Marzluff et al. 2007). Companion studies have used these land cover maps and economic development models to predict land cover change 25 years into the future (Hepinstall et al. 2008) and the potential effects of future land use and land cover change on avian communities (Hepinstall et al. 2009). Access to temporal sequences of land cover maps for large regions is important for measuring change, tracking trends, and calculating benchmarks of sustainable development (Li et al. 2009; Tregoning et al. 2002; Troyer 2002), and can be used for long-term monitoring of the effectiveness of urban planning policies such as those targeted to mitigate adverse effects of unmanaged growth on biodiversity and human living standards. In addition to the simple annualized urban sprawl index we calculated, land cover data can be used to calculate other "sprawl indices" (Bhatta et al. 2010a, b; Ji et al. 2006; Torrens 2008).

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