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The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins

Marina Alberti[a,d,*], Derek Booth[b], Kristina Hill[c], Bekkah Coburn[a], Christina Avolio[b], Stefan Coe[d], Daniele Spirandelli[d]

[a] Department of Urban Design and Planning, University of Washington, Box 355740, Seattle, WA 98195, United States
[b] Center for Water and Watershed Studies, Department of Civil & Environmental Engineering, University of Washington, Box 352700, Seattle, WA 98195, United States
[c] Department of Landscape Architecture, University of Washington, Box 355740, Seattle, WA 98195, United States
[d] Urban Ecology Research Laboratory, University of Washington, Box 355740, Seattle, WA 98195, United States

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Abstract

Landscape change associated with urbanization poses major challenges to aquatic ecosystems. Extensive studies have shown that the composition of land cover within a watershed can account for much of the variability in water quality and stream ecological conditions. While several studies have addressed the relationship between watershed urbanization and biotic integrity in streams, few have directly addressed the question of how urban patterns influence ecological conditions. These studies typically correlate changes in ecological conditions with simple aggregated measures of urbanization (e.g., human population density or percent impervious surface). We develop an empirical study of the impact of urban development patterns on stream ecological conditions in 42 sub-basins in the Puget Sound lowland region on a gradient of urbanization. We hypothesize that ecological conditions in urbanizing landscapes are influenced through biophysical changes by four urban pattern variables: land use intensity, land cover composition, landscape configuration, and connectivity of the impervious area. Using community measures of benthic macroinvertebrates as indicators of in-stream biotic integrity we examined the relationships between urban development patterns and ecological conditions in these basins. Significant statistical relationships were found between landscape patterns—both amount and configuration of impervious area and forest land—and biotic integrity of streams suggesting that patterns of urban development matter to aquatic ecosystems.

Keywords: Aquatic macroinvertebrates; Benthic index of biotic integrity; Impervious surface; Land cover; Land use; Landscape pattern; Spatial metrics; Urbanization; Watershed function

1. Introduction

Urbanization has great impacts on earth's ecology. It alters natural habitats (Marzluff, 2001) and species composition (Blair, 1996), disrupts hydrological systems (Arnold and Gibbons, 1996; Booth and Jackson, 1997), and modifies energy flow and nutrient cycles (McDonnell and Pickett, 1990; Vitousek et al., 1997; Grimm et al., 2000). Landscape change associated with urbanization, particularly sprawl, has been significant during the last half century and is expected to continue through the next decades. Across US metropolitan areas, land consumption has been outpacing population, with most urban areas expanding at about twice the rate of the population growth. Both urban development and growth in transportation infrastructure in the US has occurred on the country's most productive land (Imhoff et al., 1998).

Effects of landscape change on stream ecosystems have been extensively documented (e.g., Omerick, 1987; Roth et al., 1996; Paul and Meyer, 2001). Modifications of the land surface during urbanization produce changes in both the type and the magnitude of runoff processes. These changes result from vegetation clearing, soil compaction, ditching and draining, and covering the land surface with impervious roofs and roads (Dinicola, 1990; Poff et al., 1997; Burges et al., 1998; Konrad, 2000; Jones et al., 2000; Trombulak and Frissell, 2000). Infiltration capacity of covered areas is zero, and much of the remaining bare soil area

* Corresponding author. Tel.: +1 206 616 8667; fax: +1 206 685 9597.
E-mail address: malberti@u.washington.edu (M. Alberti).

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is trampled to a near-impervious state. Compacted, stripped, or paved-over soil also has lower storage volumes: even if precipitation can infiltrate, the soil reaches surface saturation more rapidly and more frequently (Booth, 1991; Arnold and Gibbons, 1996). Thus, overland flow is introduced into areas that formerly may have generated runoff only by subsurface flow, particularly in humid areas of low-intensity rainfall. Urban gutters, drains, and storm sewers are laid in the urbanized area to convey runoff rapidly to stream channels. Natural channels are often straightened, deepened, or lined with concrete to make them hydraulically smoother. Each change increases the efficiency of the channel, transmitting the flood wave downstream faster and with less retardation by the channel (Hollis, 1975; Barker et al., 1991; Booth, 1991; Arnold and Gibbons, 1996). These changes in upland runoff processes alter not only the magnitude of discharges but also the delivery of sediment to the stream network (Montgomery and Buffington, 1998).

Urbanization also causes riparian change. Loss of riparian habitats reduces the ability of watersheds to filter nutrient and sediments (Karr and Schlosser, 1978; Peterjohn and Correll, 1984). Clearing of streamside vegetation results in less wood entering the channel, depriving the stream of stabilizing elements that help dissipate flow energy and usually (although not always) help protect the bed and banks from erosion (Booth et al., 1997). Deep-rooted bank vegetation is replaced, if at all, by shallow-rooted grasses or ornamental plants that provide little resistance. Furthermore, the overhead canopy of a stream is lost, eliminating the shade that controls temperature and leaf litter that enters the aquatic food chain. In total, many hydrologic, geomorphic, and biological expressions of stream degradation are associated with an increase in impervious surface (Booth and Jackson, 1997; Yoder et al., 1999).

Previous studies of the impacts of urbanization on ecological systems have typically correlated changes in ecological conditions with simple aggregated measures of urbanization (e.g., human population density or percent impervious surface). They show that the composition of land cover within a watershed can account for much (but by no means all) of the variability in water quality (Hunsaker et al., 1992; Charbonneau and Kondolf, 1993; Johnson et al., 1997) and stream ecology (Whiting and Clifford, 1983; Shutes et al., 1984; Hachmoller et al., 1991; Thorne et al., 2000). Yet such correlations generally make no allowance for the location of that impervious area within the watershed, its proximity to the stream channel, or its interconnectedness with other such areas or with the channel itself.

While several studies have addressed the relationship between watershed urbanization and biotic integrity in streams, few have directly addressed the question of how urban patterns influence ecological conditions. We develop an empirical study of the impact of urban development patterns on stream ecological conditions in 42 sub-basins in the Puget Sound lowland region across a gradient of urbanization. We hypothesize that ecological conditions in urbanizing landscapes are influenced by patterns of development through biophysical change. Using community measures of benthic macroinvertebrates as indicators of in-stream biotic integrity we examined the relationships between urban development patterns and ecological conditions in these basins.

2. Relating urban patterns to stream ecological conditions

The question of how patterns of human settlements affect aquatic ecosystems is of increasing importance to both ecology (Forman, 1995; Collins et al., 2000; Grimm et al., 2000; Pickett et al., 2001) and urban planning (Collinge, 1996; Alberti, 1999; Opdam et al., 2002). Although many previous studies have addressed the relationship between watershed urbanization and the associated biotic conditions in streams (e.g., Karr and Schlosser, 1978; Arnold and Gibbons, 1996; Booth et al., 2001; Paul and Mayer, 2002), few have investigated how the *patterns* of urban development control hydrological, geomorphological, and ecological processes in human-dominated watershed. We do not know, for example, how clustered versus dispersed urban patterns affect runoff and in-stream ecological conditions, even though this design has become a mainstay of what is presumed to be a more ecologically benign style of "low-impact development."

More recently, scholars in ecology and urban planning are studying how alternative urban development patterns (e.g., areas with same density but clustered versus dispersed development) influence natural habitats, hydrological processes, energy flow, and nutrient cycles (McDonnell et al., 1997; Grimm et al., 2000; Pickett et al., 2001; Alberti et al., 2003). These studies posit that different configurations of the urban structure imply alternative effects on the mosaic of biophysical elements that control ecological processes. Urban patterns affect resource flows directly by redistributing solar radiation, water, and mineral nutrients; and indirectly by determining the resources needed to support human activities. Urban patterns also influence the feasibility of using alternative systems to supply resources and services to the urban population, thus indirectly affecting their environmental impact (Alberti and Susskind, 1997).

Since ecological processes are tightly interrelated with the landscape, the mosaic of elements resulting from human action has important implications for ecosystem dynamics. Our overarching hypothesis is that it is the pattern of human activities—extent, distribution, intensity, and frequency—and not simply the magnitude that affect stream and watershed conditions through a variety of biophysical processes. We hypothesize that differences in configuration of impervious area and forest patches, between different locations, between areas with differing degrees of connectivity, or between different types of hydrologically distinct *non*-impervious land cover can explain the variability in stream biotic conditions when controlling for land cover composition. Hydrological processes are important mechanisms that link urban patterns to stream conditions since more aggregated patterns of impervious surface may increase runoff and more fragmented patterns of forest reduce the ability of vegetation to intercept surface-water runoff. Varying urban form along the continuum of "clustered versus dispersed development" is most likely to affect aquatic ecosystems by the degree to which the upland watershed surface is pervasively dissected by new, artificial conduits of surface-water drainage (i.e., roads). This hypothesis highlights the significance of roads networks. We also anticipate that the integrity of the riparian buffer is an important predictor of stream health in urbanizing watersheds. The delivery of organic matter and solar energy varies significantly as a consequence of riparian-zone land use, and these changes interact with the extent and distribution of impervious surface and vegetative cover across the watershed.

3. Approach

For this study, we postulate that human activities are the greatest stressors at the scale of the watersheds supporting individual tributary streams. At this scale, previous research has shown that impervious surfaces result in characteristically altered and often extreme hydrologic conditions that provide an endpoint on a disturbance gradient (Booth and Jackson, 1997; Konrad and Booth, 2002). Yet total impervious area (TIA) in the contributing watershed is only a coarse predictor of biological conditions (e.g., Schueler, 1994). This parameter does not discriminate between different locations, between areas with differing degrees of interconnection, or between different types of hydrologically distinct *non*-impervious land cover. As such, it can offer only a limited suite of planning or management responses. A much broader range of landscape metrics is necessary to represent the complexity of the urban landscape (Alberti et al., 2001).

We hypothesize that ecological conditions in urbanizing landscapes are significantly influenced by four urban pattern variables: land use intensity, land cover composition, landscape configuration, and connectivity of the impervious area. Using aquatic macroinvertebrates as indicators of in-stream biotic integrity we have investigated the relationship between land use and land-cover patterns in urbanizing watersheds, and between landscape patterns and ecological conditions a varying spatial scales. We distinguish between land use attributes associated with the actual use of land parcels (i.e., residential use), and land cover representing the type of cover on the land (i.e., paved urban). The benthic index of biological integrity (B-IBI) has been used since the mid-1990s to evaluate the biological condition of Pacific Northwest streams (Fore et al., 1996; Karr and Chu, 1999; Morley and Karr, 2002). This multimetric approach evaluates biological condition by integrating measures of an empirically tested set of biological attributes (Fore et al., 1996; Rosenberg and Resh, 1993; Karr, 1998). B-IBI can be used to diagnose information from each of the 10 metrics that composes the index (see Morley and Karr, 2002 for these same data). There is vast literature that uses B-IBI to assess the ecological conditions of streams in the Pacific Northwest (Karr and Chu, 1999; Morley and Karr, 2002). In this paper we use B-IBI to synthesize overall stream conditions.

The study is organized around three questions:

(1) How do variables describing urban landscape patterns vary along a gradient of development intensity?
(2) What is the relative importance of pattern metrics in predicting changes in ecological conditions?
(3) How do the relationships of urban patterns and ecological conditions vary with spatial scale of analysis?

To answer these questions we start by establishing correlations between TIA and B-IBI in 42 sub-basins in. We then seek incremental explanatory power by adding the variables describing the four patterns. Using multivariate analysis we assess whether the models that relate TIA to ecological conditions can be improved by including patterns of urbanization. We defined the following null hypotheses:

(1) There is no significant relationship between level of basin-scale aggregation of forest cover and B-IBI values that is not already explained by the amount of forest in the basin.
(2) There is no significant relationship between basin level aggregation of paved land and B-IBI values that is not already explained by the amount of TIA in the basin.
(3) There is no significant relationship between basin level connectivity of paved patches to the stream channel through the flow path and B-IBI values that is not already explained by the amount of TIA in the basin.
(4) There is no significant relationship between roads and B-IBI values that is not already explained by the amount of TIA in the basin.

We have developed a three-step process: (1) based upon previous studies of stream biological conditions in the Puget Sound and the literature on landscape metrics we selected a number of metrics that we hypothesize are relevant to ecological conditions, (2) using stepwise regression we further reduced the set of variables to those correlated with B-IBI, and (3) developed apriori models to test our hypotheses.

4. Study area and data description

4.1. Study area

We have focused our empirical analysis of urban development patterns and their influence on aquatic ecosystems in the Puget Sound lowland region (Fig. 1). Several characteristics of this region make it an ideal site for this study. The population of the metropolitan area is among the fastest growing in the U.S. The rapidity and scale of land-use and associated land-cover changes in the Puget Sound region has resulted in a great variety of development patterns in the urban landscape, presenting a unique opportunity to investigate interrelationships between land-use processes and ecosystem dynamics.

In the Puget Sound watershed as a whole, the predominant land cover is overwhelmingly forest, while timber harvest is the dominant land use activity. The mainstem rivers that drain this landscape (with 8-digit hydrologic unit codes and drainage areas of ca. 10^3 mi^2) extend from the rugged unpopulated crests of the Cascade Range and Olympic Mountains down to the rapidly urbanizing lowlands of Puget Sound; they display a >100 year legacy dominated by forest practices and floodplain alteration, which in most cases has included channelizing, diking, draining, and filling. Many of their individual tributaries, how-

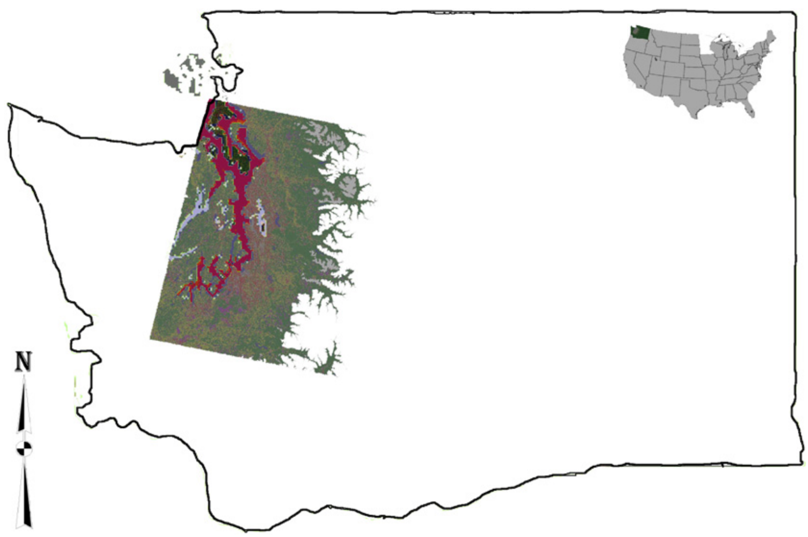

Fig. 1. Puget Sound lowland location map (47°26′N, 121°52′W).

ever, are fully contained within the gentle topography of the Puget lowland. Over that last century those smaller tributaries have been subjected first to logging, then agriculture, and now increasingly to urban development. For a large majority of these sub-watersheds, suburban, and urban development is now the dominant land use.

4.2. Selected basins

We have used 42 previously delineated sub-basins (Booth et al., 2001) with varying levels of urbanization as the basis for characterizing ecological condition. They are contained within 14 separate stream systems that drain different parts of the urban and urbanizing Puget lowland. Intrinsic differences between these streams and their contributing watersheds are modest, except for the type and distribution of land cover. At the selected sampling localities, all contributing watershed areas are between 4 and 69 km^2. Their surface geology is dominated by poorly sorted, compacted glacial till. Channels typically descend from these glaciated uplands, 50–175 m above sea level, through valleys of well-stratified granular sediment, recent alluvium, and material derived from soil creep and landsliding (Booth et al., 2003). Only two channels (May and Rock) have their uppermost headwaters in bedrock. The streams in this study all flow perennially and are classified as alluvial plane-bed or pool-riffle channels (Montgomery and Buffington, 1998) with gradients between 1% and 3%.

Mean daily discharges are not available for most of the sampling sites, because gauge records are typically sparse or absent on channels of this size. Where available, mean daily discharges are commonly between a few tenths m^3/s to 1 m^3/s, with annual runoff volumes ranging between 50 and 90 cm. About three-quarters of the annual precipitation in the region (about 100 cm on average) fall between October and March, primarily as rain in low-intensity storms of one to several days in duration. Average daily precipitation for the months of November through February ranges from 3.8 to 5.1 mm/day (0.15–0.20 in./day).

Each sub-basin was chosen as the watershed area contributing to a point with an associated, previously collected and published score using the *Benthic Index of Biological Integrity* (“B-IBI”; Booth et al., 2001; Morley and Karr, 2002) (Fig. 2, Table 1); sub-basin boundaries were determined by using a 10-m USGS Digital Elevation Model. The B-IBI is a multimetric index of biotic integrity composed of 10 metrics of taxa richness and diversity, population attributes, disturbance tolerance, and feeding and other habits of the in-stream macroinvertebrates. For the original study, three samples along the mid-line of a single riffle were collected from each site in September when stream flows were stable and low, taxa richness was high, and field crews had relatively easy access to sites (Fore et al., 1996; Morley and Karr, 2002). Invertebrates were preserved in the field in a solution of 70/30 ethanol/water and returned samples to the lab for identification under microscopy—typically to the level of genus. Following procedures first outlined for fish (Karr, 1981; Karr et al., 1986), and later for invertebrates (Ohio EPA, 1988; Fore et al., 1996), metric scores of five (values at or near what is expected at sites with little or no human influence), three (moderately divergent from condition at such sites), and one (severely divergent) were assigned to each of the 10 raw metric values. These scores were then summed to obtain a site- and time-specific B-IBI that ranged from 10 (very poor) to 50 (excellent). The benthic index of biological integrity is considered a robust method for characterizing in-stream biological condition and can help diagnose the causes of ecological impacts and suggest appropriate management actions (Karr, 1991; Karr and Chu, 1999).

4.3. Landscape data

Urban patterns in the Puget Sound lowlands were quantified using demographic, land cover, land use, and transportation data. We processed and analyzed several key data sets. *Population data* and *housing units* for 1998 (estimates) at the block level were obtained from the US Census Bureau. *Parcel data*

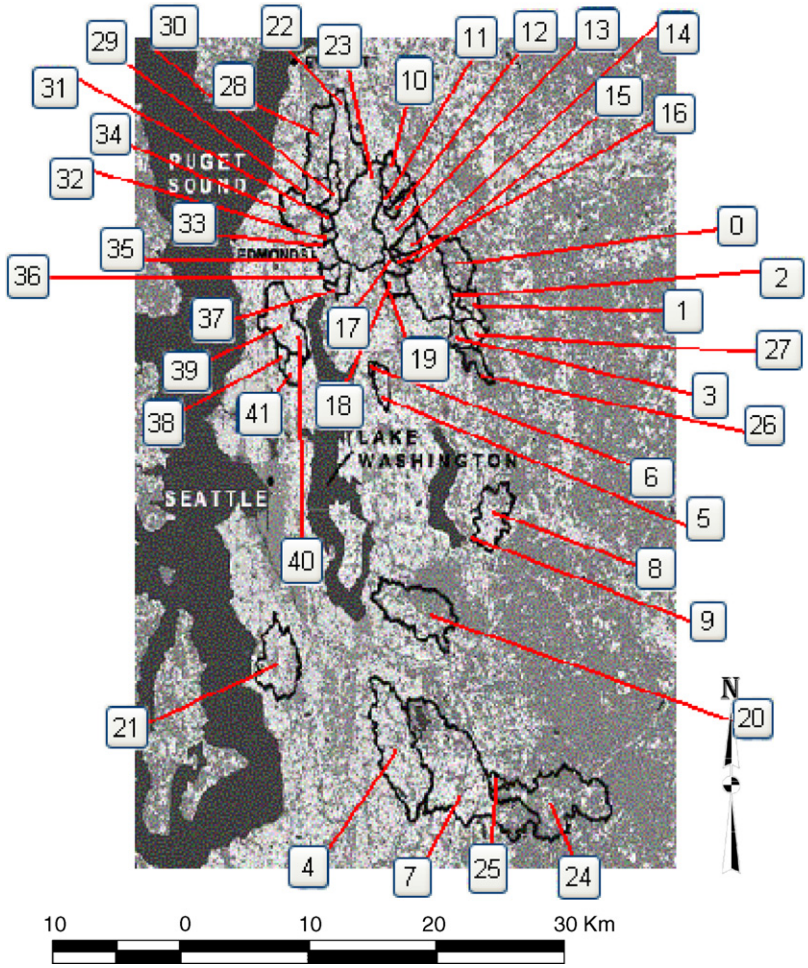

Fig. 2. B-IBI basins and Puget Sound surroundings. The numbers in the map correspond to the basin number in Table 1.

for King County and Snohomish County and the associated assessor's attribute data were obtained from King County and Snohomish GIS Offices. We developed land use maps at the parcel scale by using land use data from the assessor data files. This involved the development of a protocol for standardizing error checking, cleaning, and processing of parcel data sets. We have developed and implemented a land use classification system that includes nine land-use classes based on similarity of functional land use characteristics. Multiple classes were collapsed into nine categories (Fig. 3): (1) Single family Residential (SFR), (2) Multifamily Family Residential (MFR), (3) Commercial, (4) Institutional, (5) Industrial, (6) Open Space, (7) Transportation, (8) Mixed Use (Residential and Commercial), and (9) Water. The *road network* data for 1998 were obtained from the Puget Sound Regional Council.

Land cover data for 1998 were interpreted from Landsat Thematic Mapper (TM) imagery for the Puget Sound region for 1998 (Fig. 4; Hill et al., 2003). Landsat TM data were preprocessed to mosaic the two image swaths (path 46: row 26–27, and path 47: row 26–27) and corrected for the effects of atmosphere and topography. The classification procedure creates a seven-class land cover system, which discriminates between 3 classes of urban land cover characterized by varying levels of impervious surface and vegetation coverage. The approach taken for this classification is to characterize the urban classes as mixed classes since the resolution of Landsat TM data in urban areas does not allow for effectively capturing the heterogeneity of the urban landscape. These classes are determined by further characterizing the pixel composition. The three urban classes include: *paved urban* (>60% paved cover), *grass/shrub urban* (characteristic of newer suburban areas with paved area between 20% and 60%, and relatively large lawn coverage >25%) and *forested urban* (characteristic of mature residential neighborhoods with paved area between 20% and 60%, and a high degree of canopy cover >20%) (Hill et al., 2003). When examined together, these classes are further referred as *urban land.* Other land cover classes include: forested land, grass/shrub/crops, bare soil, and water (Fig. 3). An accuracy assessment was performed using 350 randomly selected clusters of 3 × 3 pixels. The accuracy assessment was then performed through systematic visual inspection of these clusters of homogeneous land cover using 1-m 1998 digital orthophoto. Overall accuracy was estimated at 77%. The percent of *grass*, *trees*, *and impervious area* in the various land cover classes were extracted from a visual analysis of the 350 randomly selected clusters and applied to quantify the three variables at the various scales (Table 2).

Table 1
B-IBI sub-basin locations and scores

Site#	Stream[a]	B-IBI[b]	Drainage area (km^2)	Nearest city	%Trees	%TIA
1	Big Bear	32	12.68	Woodinville	72	2
2	Big Bear	36	17.13	Redmond	7	19
3	Big Bear	34	20.73	Redmond	68	21
4	Big Bear	28	61.14	Redmond	62	24
5	Big Soos	26	42.02	Auburn	37	38
6	Forbes	16	5.09	Kirkland	29	48
7	Forbes	16	5.77	Kirkland	3	48
8	Jenkins	32	69.30	Covington	52	31
9	L. Jacobs	30	15.86	Sammamish	46	34
10	L. Jacobs	22	15.93	Sammamish	46	34
11	Little Bear	36	8.13	Mill Creek	49	31
12	Little Bear	40	9.86	Mill Creek	5	3
13	Little Bear	34	11.77	Bothell	52	29
14	Little Bear	[c]	23.96	Bothell	55	27
15	Little Bear	28	28.75	Woodinville	55	27
16	Little Bear	22	30.36	Woodinville	54	27
17	Little Bear	16	31.62	Woodinville	54	28
18	Little Bear	30	35.44	Woodinville	53	29
19	Little Bear	24	39.59	Woodinville	51	3
20	Little Bear	22	39.93	Woodinville	5	31
21	May	24	29.54	Renton	63	23
22	Miller	12	22.02	Normandy Park	19	57
23	North	[c]	20.22	Mill Creek	37	43
24	North	22	57.09	Bothell	39	39
25	Rock	[c]	40.63	Maple Valley	78	13
26	Rock	48	42.90	Maple Valley	77	14
27	Seidel	36	5.48	Redmond	87	1
28	Struve	34	4.38	Redmond	57	28
29	Swamp	26	15.17	Lynnwood	37	43
30	Swamp	28	21.44	Lynnwood	38	42
31	Swamp	30	27.48	Lynnwood	37	41
32	Swamp	26	29.00	Brier	38	41
33	Swamp	[c]	30.60	Brier	37	41
34	Swamp	[c]	45.85	Brier	33	45
35	Swamp	20	15.24	Brier	23	54
36	Swamp	[c]	50.74	Kenmore	34	44
37	Swamp	24	53.42	Kenmore	34	44
38	Swamp	22	58.06	Kenmore	35	43
39	Thornton	14	2.30	Seattle	17	61
40	Thornton	10	18.46	Seattle	22	54
41	Thornton	10	18.47	Seattle	22	54
42	Thornton	12	25.48	Seattle	22	54

[a] Basins are listed alphabetically.
[b] Range from 10 (very poor) to 50 (Excellent).
[c] Not available.

5. Landscape analysis

5.1. Pattern metrics

Urban ecological gradients in the Puget Sound metropolitan region were quantified using land-use and land-cover pattern metrics. We measure four aspects of the landscape including: land use intensity, landscape composition, landscape configuration, and connectivity (Table 3). We measure land-use intensity using metrics developed in the urban planning literature (Cervero, 1989; Alperovich and Deutsch, 1992; Batty and Longley, 1998). Landscape composition and configuration are quantified using landscape ecology metrics. Researchers in landscape ecology have developed a large number of metrics for quantifying such patterns and their effects on disturbance regimes (O'Neill et al., 1988; Turner, 1989; McGarigal and Marks, 1995; McGarigal et al., 2002). We also developed two new spatial metrics to measure basin-scale connectivity of the impervious surface to the stream network along the flowpath.

Table 2
Percent trees, grass, and TIA by land cover type (from Hill et al., 2003)

	%Trees	%Grass	% Impervious area
Forested urban	39	23	39
Grass urban	4	21	74
Paved urban	5	2	92
Grass/shrub/crops	1	94	5
Water	0	0	0
Bare	2	0	98
Forest	96	1	3

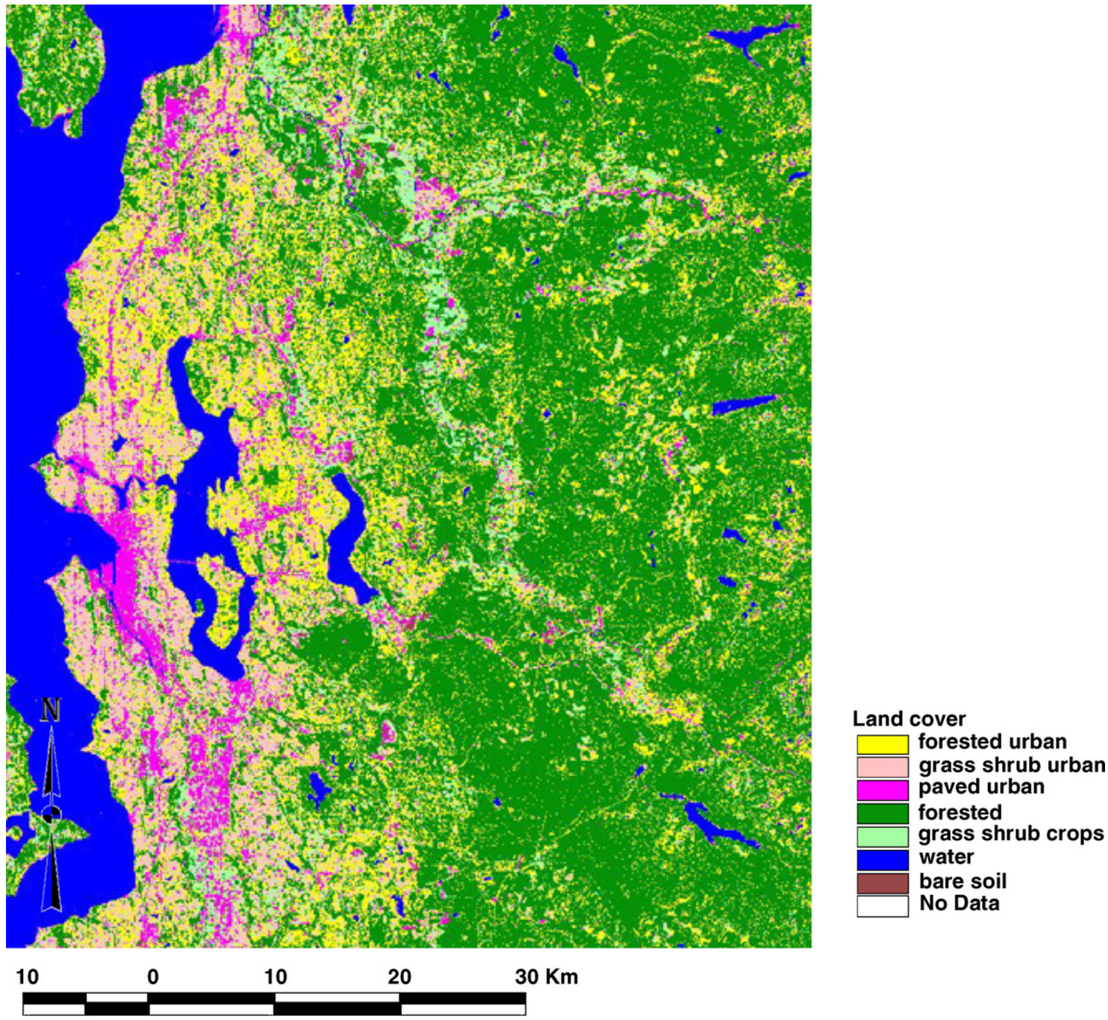

Fig. 3. Puget Sound land cover classification from 1998 LANDSAT image (from Hill et al., 2003).

Land-use intensity metrics include percent area of a specific land-use class, population density, housing unit density, and various metrics of transportation infrastructure. Land-use patterns in basins were quantified by intersecting parcel data and sub-basins to determine percent land use types in each sub-basin. Population and housing unit density for each census block or block section were calculated and then assigned to each basin by intersecting the census block coverage with sub-basins. The number of road crossings per stream kilometer was determined by intersecting the roads line layer with the streams line layer, and then summarizing the clipped roads with a count operation to count the number of road segments. The upstream distance to a road crossing was measured using the ArcView measuring tool to measure the distance along the stream network from the

Table 3
Selected landscape metrics

Intensity metrics	Composition metrics	Configuration metrics	Connectivity metrics
%Single family residential	%Forested urban	Contagion	#Road crossing/km of stream
%Multi family residential	%Grassy urban	Mean patch size urban	Median distance of paved patches through the flow path
%Commercial	%Paved urban	Mean patch size forest	Weighted median distance of paved patches through the flow path
%Institutional	%Grass/shrub/crops	Aggregation index urban	
%Industrial	%Forest	Aggregation index forest	
%Open space	%Water	Percent like adjacent index urban	
%Transportation	%Bare soil	Percent like adjacent index forest	
%Mixed use	%Grass		
Population density	%Trees		
Housing unit density	%TIA		
Road density	Shannon index		
Road intersection density			

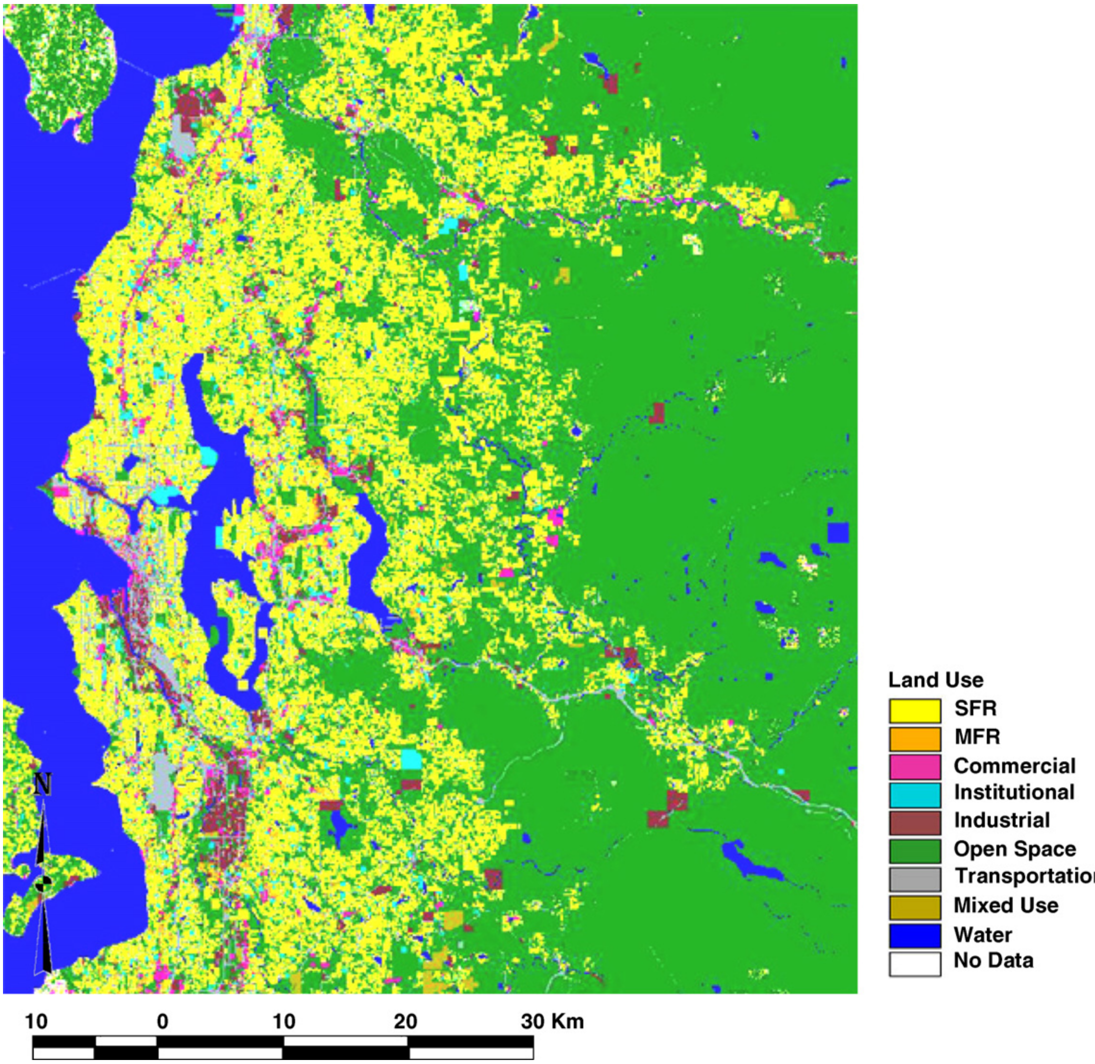

Fig. 4. Puget Sound land use classification from parcel data.

sampling point to the nearest upstream road crossing along the main-stem channel. The streams layer was also summarized for each sub-basin to get the total stream length per sub-basin. The attribute tables were then exported to Excel to determine the number of road crossings per km of stream for each sub-basin. This metric gives equal weight to all types of roads (i.e., highway versus residential).

We apply several landscape metrics to measure urban landscape composition and configuration (Table 4). First, we measured landscape composition by the percent urban land as classified in the land cover map for 1998. Then we quantified the percent impervious area, percent trees, and percent grass within each sub-basin. The percent of land cover (percent land) occupied by each patch type (i.e., paved, forest, or grass) is considered an important indicator of ecological conditions since some ecological properties of a patch can be influenced by the composition of the patches and abundance of similar patches within the landscape. Percent Land is the sum of the area of all patches of the corresponding patch type divided by total area of the basin or other sub areas. The Shannon diversity index (SHDI) measures the number of land cover classes in the landscape.

We then applied four metrics to measure urban landscape configurations: mean patch size (MPS), contagion (C), aggregation index (AI), and percentage-of-like-adjacency (PLADJ) (O'Neill et al., 1988; Turner, 1989; McGarigal and Marks, 1995). Mean Patch Size is the sum of the areas of all patches divided by the number of patches. Contagion is the probability that two randomly chosen adjacent cells belong to the same class. This is calculated by the product of two probabilities: the probability that a randomly chosen cell belongs to category type i, and the conditional probability that given a cell is of category type i, one of its neighboring cells will belong to a different type. We quantify landscape configuration also using aggregation (AI) and PLADJ indices with Fragstats (Version 3.0, McGarigal et al., 2002). AI equals the number of like adjacencies involving the corresponding class, divided by the maximum possible number of like adjacencies of that class. PLADJ equals the sum of the number of like adjacencies for each patch type, divided by the total number of cell adjacencies in the landscape; multiplied by 100 (to convert to a percentage).

We also characterized the spatial configuration of the sub-basins by measuring the connectivity of the impervious surfaces

Table 4
Pattern metrics

Landscape metrics	Equations
Percent land	
Sum of the area of all patches of the corresponding patch type divided by total area of the basin	$\text{PLAND} = Pi = \frac{\sum_{j=1}^{n} aij}{A}(100)$
Contagion	
Probability of two cells of type i and j to be adjacent where m is the number of land cover types, P_{ij} is the proportion of cells in land cover i adjacent to cells of type j and $2\ln(m)$ is the maximum when all possible adjacencies of class i and j occur with equal probability.	$C = \frac{2\ln(m)+\sum_{i=1}^{m}\sum_{j=1}^{m} P_{ij}\ln P_{ij}}{2\ln(m)}$
Mean patch size	
Sum of the areas of all patches divided by the number of patches.	$\text{MPS} = \frac{\sum_{j=1}^{n} a_{ij}}{n_i}$
Shannon diversity	
Minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion.	$\text{SHDI} = -\sum_{i=1}^{m}(P_i - \ln P_i)$
Percent like adjacency	
Equals the sum of the number of like adjacencies for each patch type, divided by the total number of cell adjacencies in the landscape; multiplied by 100.	$\text{PLADJ} = (100)\left(\frac{g_{ii}}{\sum_{k=1}^{m} g_{ik}}\right)$
Aggregation index	
Equals the number of like adjacencies involving the corresponding class, divided by the maximum possible number of like adjacencies involving the corresponding class; multiplied by 100.	$\text{AI} = (100)\left[\frac{g_{ii}}{\max\rightarrow g_{ii}}\right]$

Sources: O'Neill et al. (1988), Turner (1989), McGarigal and Marks (1995), and McGarigal et al. (2002).

to the stream channel itself. We measured the *connectivity* of impervious surface to the stream network to determine *hydrological distance* and explore its relationship to stream quality. We measured connectivity by calculating the closest distance from urban land cover to streams and road networks along the flow path. We determine flow path using a 10 m Digital Elevation Model to generate the flow direction and accumulation. Distance values were extracted for three land cover types: forested urban, grassy urban, and paved urban. In addition we developed an index of *weighted connectivity* which takes into account the land cover through the flowpath. This was obtained by measuring flowlength in Arc Grid using a weight grid. Flowlength in Arc Grid assigns to each pixel a distance in pixels from the pixel. We determined the distance per each pixel of different land cover and used a weight grid to account for the potential runoff of different land cover type. The weight grid adds a "cost distance" value to each pixel. Using the weight grid, distance for each pixel is determined not only by the direction of flow, but also by the weighted value of the associated pixel. We used land cover data and the percent impervious in each land cover type to weight our values. We then extract median flowlength distance for each sub-basin. In addition, we calculated the percent area for each urban land cover class on 2000 pixels or more of upslope pixels that flow into one pixel. We examined Median Distance by sub-basin versus B-IBI. We also examined whether median distance would improve the predictive power of percent TIA.

5.2. Multiple-scale analysis

Since most metrics are scale dependent (e.g., relative to the measurement scale used) or are relevant to processes operating only at specific spatial scales (Krummel et al., 1987; O'Neill et al., 1988; Bartel and Brenkert, 1991), we systematically analyzed the relationships between landscape patterns and B-IBI across nested scales. We performed the scale analysis only on a selected set of composition and configuration metrics to observe their behavior at multiple scales (see Table 6).

Scale concerns can be thought of both in terms of resolution (size of the minimum mapping unit) and geographic extent of the study area. Resolution expresses the extent to which spatial qualities of a map have been generalized. Geographic extent of a study expresses a hypothesis about the area contributing to a particular ecological process. The resolution of the data used to estimate the metrics is 30 m. We developed a multiple scale analysis using five nested scales: local riparian zone: 100, 200, and 300 m riparian widths; and basin scale (Fig. 5). We determined the riparian buffer using distance from the flow path based on a 10 m Digital Elevation Model to generate the flow direction and accumulation. Local riparian zones were defined as 100 m riparian buffer 1 km upstream from the B-IBI measurement point. The multiple-scale landscape analysis was performed by intersecting the parcel data, the land cover data, and Census blocks separately with the five vector boundary files representing the five scales of analysis developed for each sub-basin. Then the coverage was intersected with the vector basin coverages using ArcGIS. Parcel area for each actual land use was used to determine the percent land use within the sub-basin and buffer zones. For the land cover we overlaid the land cover grid with the vector files and summarized the number of pixels by each land cover class within the basins and buffer zones. For the population and housing density variables we used census blocks. Census blocks were intersected with the vector boundary files and the popula-

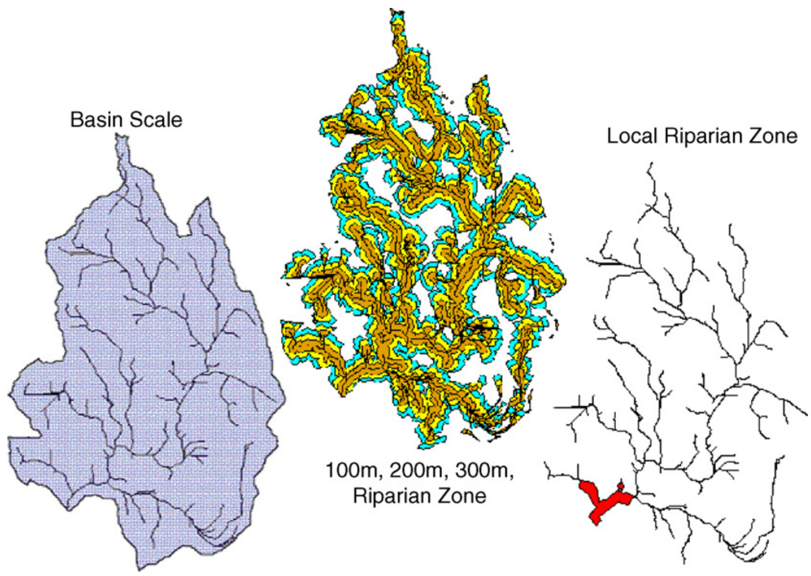

Fig. 5. Different spatial scales of analysis (e.g., Miller basin).

tion and number of housing units of each block or block section were calculated by multiplying density by area for that block or portion of the block falling with each defined boundary.

5.3. Statistical analysis

We tested relationships between metrics of urban landscape patterns and B-IBI in the selected sub-basins using a two-step process. First using stepwise regression analysis we reduced the set of variables to those correlated with B-IBI. Then we developed apriori models to test our hypotheses. We conducted an exploratory analysis using forward stepwise regression (P-value = 0.05 to enter and 0.10 to remove). We examined models using composition and configuration metrics for urban and forest. We did not include urban and forest land cover together since they are highly correlated and their relationships to B-IBI are the inverse of each other. We then developed a set of apriori models to test our hypotheses. Since we know that percent TIA is an important variable, we developed a hierarchical model starting with percent TIA and tested the significance of entering configuration variables. We added one pattern metric at a time and compared them using adjusted R^2 and the Akaike Information Criterion (AIC). We then calculated the partial correlation coefficient for the pattern metric to see how much additional variance it explains over percent TIA alone. To address issues of multicollinearity we performed a correlation analysis among the variables and estimated the Variance Inflation Factor (VIF). VIF values were high but still acceptable (max < 10). Since high multicollinearity leads to high covariance between regression coefficients of the related variables, it is difficult to separate out

Table 5
Statistics summary of gradient of metrics represented by sub-basins

	%Grass	%Trees	%TIA	
(a) Statistics summary for the %grass, %trees, and %TIA metrics for the 42 sub-basins				
Mean (%)	12	46	36	
Median (%)	12	48	32	
Minimum (%)	4	17	10	
Maximum (%)	17	87	61	
	PLADJ (urban)	PLADJ (forest)	AI 1 (urban)	AI 2 (forest)
(b) Summary statistics for percent-like-adjacency (PLADJ) and aggregation index (AI)				
Mean	77.69	71.46	78.47	72.61
Median	77.86	72.66	78.31	73.47
Minimum	50.89	44.44	52.78	50.91
Maximum	92.17	91.09	93.28	92.38
	Road density (km/km^2)	#Road crossings (#crossings/km stream)		Intersection density (#/km^2)
(c) Summary statistics for road density metrics				
Mean	6.61	2.12		28.41
Median	6.20	2.01		25.17
Minimum	0.62	0.60		0.73
Maximum	13.26	3.84		64.02

Table 6
R^2 of pattern metrics at multiple scales

Transformed variable	Basin	300 m	200 m	100 m	Local
arcsin(sqrt(%grass)	0.52	0.49	0.52	0.56	0.02**
arcsin(sqrt(%trees)	0.60	0.61	0.62	0.64	0.07**
arcsin(sqrt(%TIA)	0.61	0.61	0.62	0.63	0.08**
log(population_density)	0.55	0.55	0.56	0.57	
log(housing_density)	0.55	0.56	0.57	0.58	0.40
arcsin(sqrt(PercentLikeAdjacency_urb)	0.63	0.62	0.62	0.57	0.28
arcsin(sqrt(PercentLikeAdjacency_for)	0.63	0.61	0.60	0.40	0.36
arcsin(sqrt(Aggregation Index_urb)	0.63	0.62	0.38	0.64	0.30
arcsin(sqrt(Aggregation Index_for)	0.65	0.64	0.63	0.63	0.31
arcsin(sqrt(MeanPatchSize_urb)	0.64	0.60	0.66	0.58	0.44
arcsin(sqrt(MeanPatchSize_for)	0.60	0.66	0.57	0.66	0.45
Road density	0.67	0.65	0.63	0.65	0.31
Median hydrological distance	0.25*				
log(#road crossings)	0.66				

R^2 of simple regressions between pattern metrics and B-IBI (all $P < 0.001$) except the one noted with an asterisk. All $P < 0.001$.
* $P < 0.01$.
** Not significant $P > 0.05$.

the effects of each variable and can create unstable coefficients. This requires particular caution in interpreting the results. To meet the assumptions of normality for all variables of parametric tests, we used two types of transformations: log (# of road crossings, mean urban, and forest patch size) and arcsine square root (percent land cover, aggregation indices and percent like-adjacency, contagion and Shannon index).

6. Results

The following section starts by characterizing the relationships between land use and land cover in the 42 basins (Table 5). We then describe the relationships between the pattern metrics and B-IBI (Table 6) and the results of apriori models (Table 7).

6.1. Land use and land cover

The sub-basins represent a gradient of urbanization ranging from 10% impervious area in Seidel Creek to 61% in Thornton Creek (Table 5). Conversely percent trees in the sub-basins vary from 17% to 87%. The basins also vary with respect to the intensity of land uses and road infrastructure density. The variability in the level of development across these basins is also reflected in the landscape configuration metrics as measured by the AI for the urban and forest cover which vary, respectively, between 53 and 93 (AI of urban) and between 44 and 91 (AI of forest).

The distributions of land uses across basins with different percent of impervious surface indicate complex relationships between land use and land cover in the 42 drainage basins (Fig. 6). Different land use parcels have different amounts of

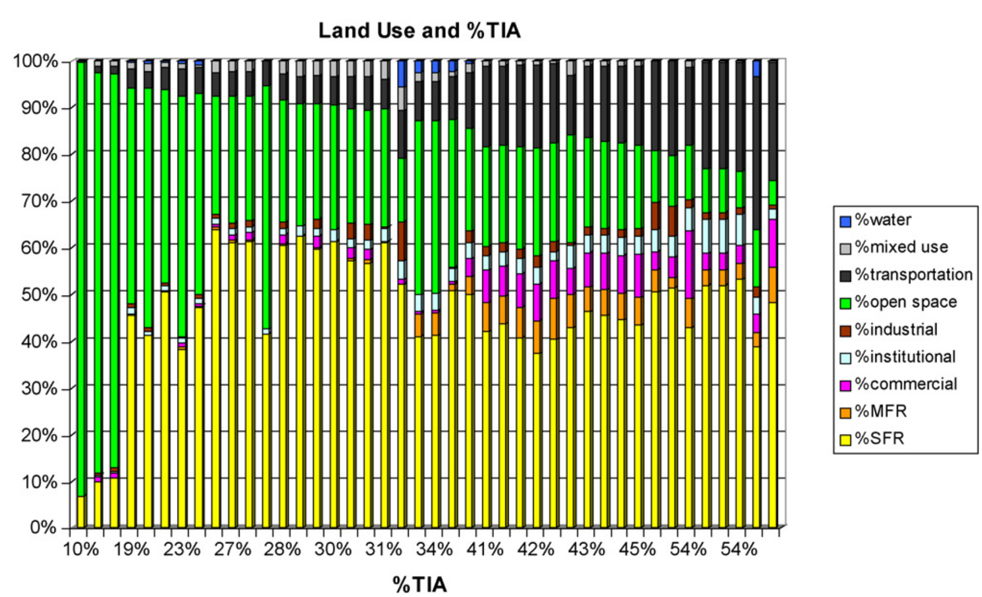

Fig. 6. Land use in each sub-basin and percent total impervious surface. Please note that the %TIA across the basins represented on the x-axis is not on a consistent interval.

Table 7
Apriori model results

Model rank	Dependent	Independent	adj. R^2	AIC values	ΔAIC
1	B-IBI	LOG_MPS + LOG_Road Cross	0.70	116.32	0
2	B-IBI	LOG_Road Crossings	0.66	121.12	4.80
3	B-IBI	AS_TIA + LOG_Road Cross	0.66[a]	121.68	5.36
4	B-IBI	AS_TIA + LOG_MPS Urban	0.63[a]	123.30	6.98
5	B-IBI	LOG_MPS Urban	0.63	124.90	8.08
6	B-IBI	AS_TIA	0.60	126.61	10.30

BIBI: Benthic index of biotic integrity; MPS: mean patch size; TIA: total impervious surface; AS: ArcSin. All models are significant at <0.001.
[a] AS_TIA not significant.

impervious surface depending on the land use type and pattern of development. Single-family residential parcels have generally significantly lower amounts of impervious surface than multi-family parcels, although these parcels may accommodate a much larger number of households. Even greater is the percentage of impervious surface on mixed-use parcels, where residential and commercial activities are located, and industrial parcels. On the other hand, high percentage of forest cover is found in single-family residential whereas this drops significantly in the other land use types. It is important to notice that there can be high variability of land cover within the same land use type. This depends on parcel size, location of the parcel over an urban-to-rural gradient, and year built.

The amount and aggregation of impervious surface can be explained by population density, housing density and transportation infrastructure in the basins. Percent impervious area is highly correlated with percent transportation use ($R^2 = 0.93$, $P < 0.001$), housing density ($R^2 = 0.92$, $P < 0.001$) and population density ($R^2 = 0.90$, $P < 0.001$). Also 91% of the variation in aggregation of urban land measured by the Aggregation Index could be explained by percent transportation ($R^2_{\text{(adjusted)}} = 0.88$, $P < 0.001$) and population density ($R^2_{\text{(adjusted)}} = 0.91$, $P < 0.001$). These results show that land development typology have different impacts on the amount of natural land cover that can be preserved and level of fragmentation that will be generated under different land-use scenarios.

6.2. Land use intensity

Patterns of biological conditions in 42 sub-basins were best predicted by basin scale road density ($R^2 = 0.67$, $P < 0.001$) and the number of road crossings per km up stream from the B-IBI measurement points ($R^2 = 0.66$, $P < 0.001$) (Fig. 7, Table 6). The data show a linear relationship between number of road crossings and biological conditions in the stream, with B-IBI values approaching poor biological conditions after two crossings per kilometer. Strong relationships also were found between B-IBI and population density at both the basin and local scale ($R^2 = 0.55$, $P < 0.001$). Statistically significant relationships were also found between land use and B-IBI, which strength varies with diverse patterns of land use intensity ranging from percent Transportation ($R^2 = 0.56$, $P < 0.001$), percent Institutional ($R^2 = 0.44$, $P < 0.001$), percent Commercial ($R^2 = 0.20$, $P < 0.001$), percent MFR ($R^2 = 0.18$, $P < 0.001$), to percent Mixed use ($R^2 = 0.12$, $P < 0.001$).

6.3. Landscape pattern

Urban ecological gradients in the Puget Sound metropolitan region can be quantified using land-use and land-cover pattern metrics (Alberti et al., 2001). The pattern metrics selected are useful to describe the composition and spatial configuration of urban development in our 42 basins. Our regression models clearly indicate that land uses and housing density on an urban-to-rural gradient are good predictors of land-cover composition and configuration. These results show that land development patterns have different impacts on the amount of natural land cover that can be preserved and the level of fragmentation that will be generated under different land-use scenarios. All the pattern variables were significantly related with B-IBI scores including Mean Patch Size urban ($R^2 = 0.64$, $P < 0.001$), Aggregation Index of forest ($R^2 = 0.65$, $P < 0.001$), PLADJ forest ($R^2 = 0.63$, $P < 0.001$), percentage TIA ($R^2 = 0.61$, $P < 0.001$), MPS forest

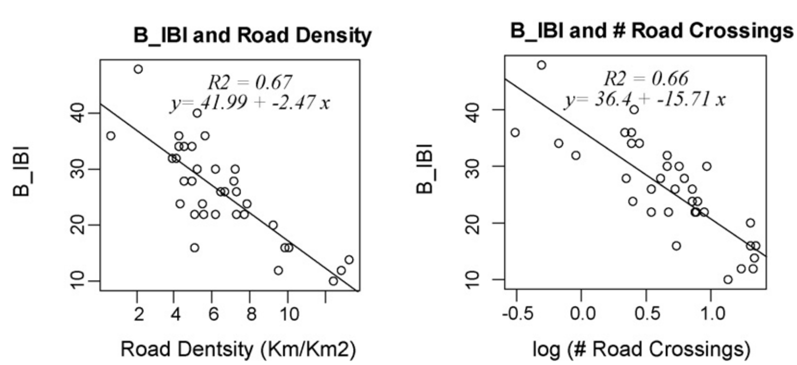

Fig. 7. Relationships between B-IBI and road network.

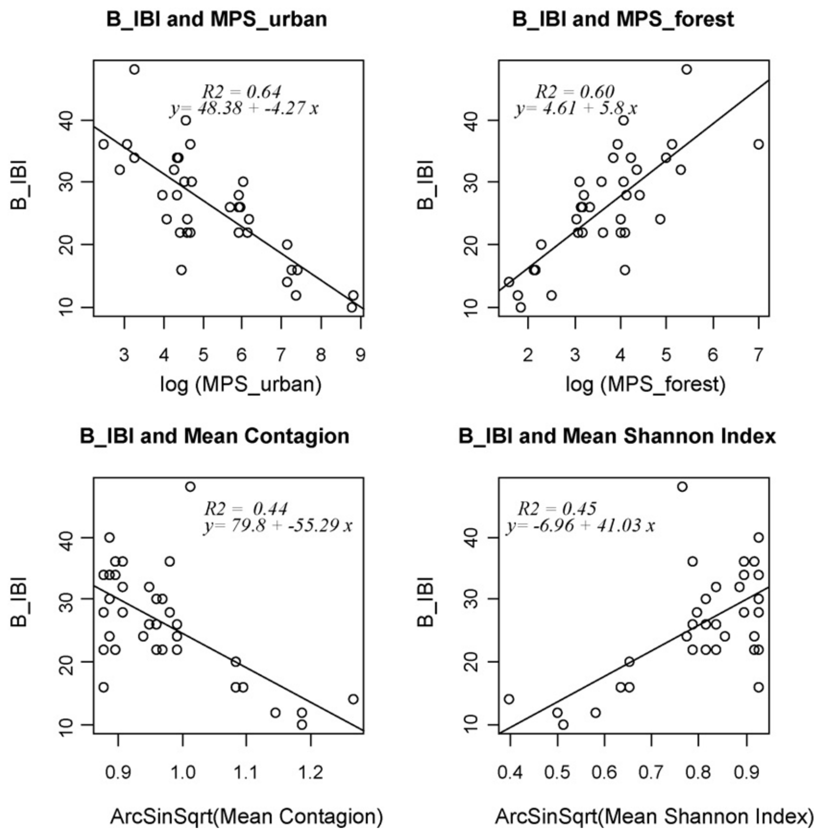

Fig. 8. Relationships between contagion, shannon index, and mean patch size (MPS) and B-IBI.

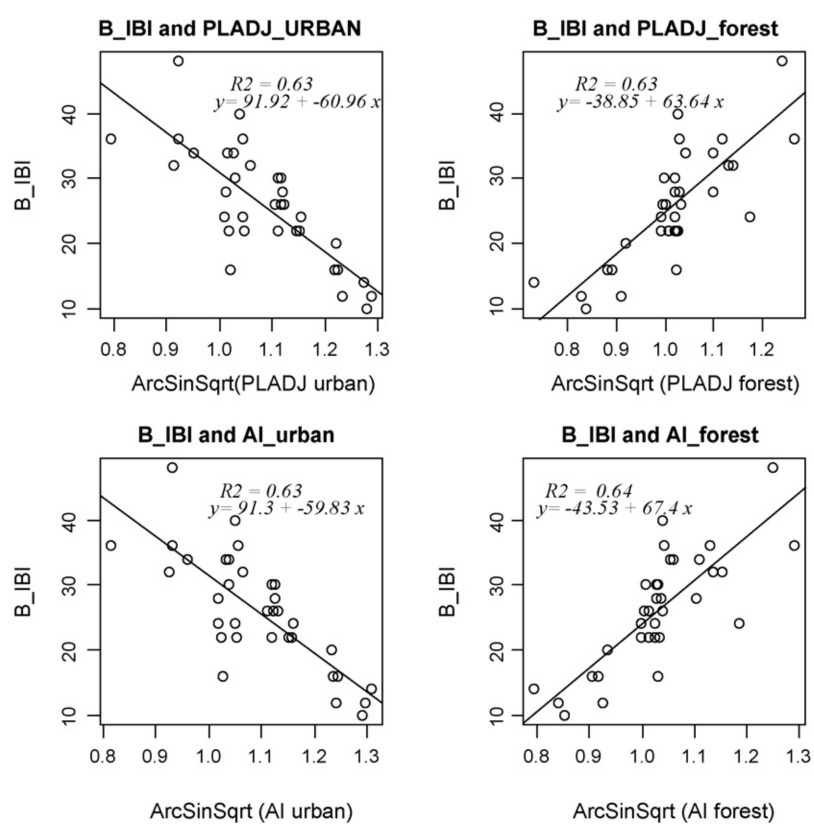

Fig. 9. Percentage of like adjacencies, aggregation index (AI), and B-IBI.

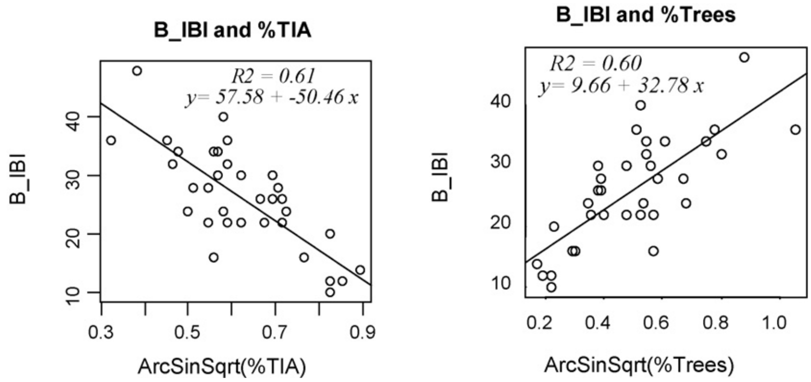

Fig. 10. Relationships between percent TIA (total impervious area), percent trees, and B-IBI.

($R^2 = 0.60$, $P < 0.001$), AI urban ($R^2 = 0.60$, $P < 0.001$), PLADJ urban ($R^2 = 0.63$, $P < 0.001$), and percentage forest ($R^2 = 0.63$, $P < 0.001$) (Figs. 8–10).

The results from our apriori models (Table 7) show that MPS of urban land cover and road crossings together do a much better job than percent TIA alone in explaining the variance in B-IBI. The models vary between a R^2 of 0.70 for model 1 (# of road crossings and MPS) and Akaike of 116.32 and a R^2 of 0.60 and Akaike of 126.61 for model 6 (percent TIA). When including MPS of urban land cover and percent TIA, although the overall model is significant ($P < 0.001$), percent TIA becomes insignificant because of its high correlation with MPS. MPS and # of road crossings are both significant alone and when are included in the model together and they explain more than percent TIA alone.

6.4. Connectivity

We correlated the median flow distances of paved patches within each sub-basin to B-IBI scores. We use both the median flowlength distances and the distance weighted by the land cover through the flowpath. Median flow distance is correlated with B-IBI ($R^2 = 0.25$, $P < 0.01$) but do not improve the explanatory power of percent TIA, since it is highly correlated with percent TIA ($r = 0.57$). Because road networks enhance the land cover connectivity through flow paths across the urban landscape, the distinction of total impervious area and effective impervious area is not as important in highly urbanized areas as it is in less urbanized areas. The landscape becomes increasingly connected with increasing impervious surface.

6.5. Effect of scale

The results of the regression analysis show that all variables are significant at four scales except at the local riparian scale. The only variable significant at the local riparian scale is housing density. Our results clearly indicate that it is the basin landscape patterns that significantly influence stream biotic integrity. The scale of analysis of sub-basin landscape patterns does not show however a powerful trend. The differences in R^2 across scale are too small to be of significance (Table 6). While landscape configuration metrics (AI and PLADJ) had slightly higher R^2 at the sub-basin scale and landscape composition metrics (percent TIA and percent Trees) had slightly higher R^2 at the riparian scale, the differences are too small to be of significance.

7. Discussion

7.1. Multiple stressors

Over the past decade, numerous studies have linked urbanization with aquatic ecosystem condition (Hunsaker et al., 1992; Charbonneau and Kondolf, 1993; Booth and Jackson, 1997; Wang et al., 1997; Karr, 1998; Yoder et al., 1999; Finkenbine et al., 2000; Thorne et al., 2000; Booth et al., 2002). Although impervious surface emerges as perhaps the most prominent stressor, it is clear that there is no best single variable that explains complex relationships between urban development and ecological conditions in watersheds. Aquatic ecosystems can be altered by human actions in several ways (Karr, 1995). Our study confirmed the strong correlation between urban land cover and B-IBI found by others (Morley and Karr, 2002). TIA explains a large part of the variance in B-IBI across the 42 basins. However, while TIA is highly correlated with multiple factors in urbanizing landscapes (i.e., population density, housing density, and road density), TIA does not fully represent the complex relationships between land use and land cover. Different landscape patterns (i.e., mean patch size of urban land) and connectivity (i.e., # of road crossings) contribute to ecological conditions across basins.

7.2. Roads as key urban stressors

The findings confirm that roads are a key stressor in urbanizing landscapes (Jones et al., 2000; Trombulak and Frissell, 2000). This is particularly relevant given that the land use/land cover analysis indicates that road intensity is correlated with total impervious surface in basins. Since roads increase impervious surface, and ditches are built to channel water from roads into streams, the rate of water runoff is higher in basins with a greater amount of roads. A more specific result of our study is that both road density and number of road crossings are better predictors of B-IBI than raw total impervious area. In particular, road crossings are a better predictor than road density. The important effect of road crossings can be related to the cumulative effect of various road-related stresses including streambanks and channel alteration, leaking of petroleum products, and increased pollution and sediment loadings.

7.3. Landscape fragmentation

The study clearly indicates that at the scale of the watersheds supporting individual tributary streams, patterns of urban development affect ecological conditions on an urban-to-rural gradient. At this scale, previous research has shown that impervious surfaces result in characteristically altered and often extreme hydrologic conditions that provide an endpoint on a disturbance gradient (Meyer et al., 1988; Booth and Jackson, 1997; Konrad and Booth, 2002). However, percent impervious area and percent forest in the contributing watershed is only a coarse predictor of biological conditions in streams, in part because hydrological change is only one of several factors that affect stream biota. The aggregation of urban land and forest land cover may explain some of the variability in B-IBI not explained by TIA. Significant statistical relationships are found between selected landscape patterns and ecological conditions in streams. While the findings clearly suggest that patterns of urban development matter to watershed function, this relationship does not indicate a specific threshold but shows that both the increase in percentage impervious surface and its aggregation both have a direct impact on stream macroinvertebrates. In particular, as the probability of urban land cover being adjacent rises from 50% to 100%, typical B-IBI values decline from 50 (excellent) to 10 (very poor). However, because of the high correlation between the aggregation index of paved urban and amount of paved urban in the basins we cannot reject the hypothesis that there is not significant relationship between basin level aggregation of paved land and B-IBI values that is not already explained by the amount of TIA in the basin. We do show however that mean patch size and number of road crossings are better predictors than %TIA alone.

7.4. Basin and riparian effects

Our multiple-scale analysis aimed at discriminating across patterns that operate at different scales—from riparian local zone to basin. Since landscape metrics are scale-dependent, we systematically examined the relationship between each variable and B-IBI at each scale. Except for the local riparian zone, all variables are highly correlated with B-IBI across the various scales. In our study however we were not able to determine whether the effects of land cover composition and configuration vary with scale. Particularly since the riparian and sub-basin variables are closely correlated ($R = 0.95$, $P < 0.001$), it is difficult to discriminate between riparian and sub-basin effects because of the nested effect, even though the processes that affect aquatic ecosystems are clearly different.

8. Conclusions

While the processes of urbanization and development are linked to ecological degradation, they are by no means homogenous or uniform in terms of their explicit spatial patterns or implications to biophysical functioning. In this study we postulate that urbanization can be characterized according to the four different dimensions of landscape composition, landscape configuration, land-use intensity, and connectivity. It is necessary to understand the nature of the relationships and interactions between these dimensions before trying to associate them individually to ecological conditions, and perhaps more importantly, before management strategies target any one measure for guiding or limiting development.

The findings of this study indicate significant statistical relationships between urban landscape patterns—both amount and configuration of impervious area and forest patches—and ecological conditions in streams. Although many studies have addressed the relationship between urbanization and aspects of ecosystem function (e.g., Karr et al., 1985), few have asked directly how patterns of urban development affect aquatic ecosystems. Most studies on the impacts of urbanization on environmental systems correlate changes in environmental systems with simple aggregated measures of urbanization (e.g., human population density, percent impervious surface). However, these metrics are only coarse predictors of biological conditions and do not discriminate between different landscape patterns. As such, they can offer only crude predictions of conditions and a limited suite of planning or management responses.

In this paper we confirm that percent impervious surface does explain a great part of the variance in B-IBI across the sub-basins, but show that our hypothesized relationship between landscape pattern and stream biological condition can be better captured by other variables that describe the configuration and connectivity of the landscape such as mean patch size and number of road crossings as stated in Hypotheses 1, 2, and 4. Both mean patch size of urban land cover and number of roads crossing the stream explain part of the variance not explained by TIA alone. Important other configuration variables that are significantly correlated with B-IBI are aggregation index and percent-like adjacencies of urban land cover indicating that aggregated impervious surfaces have a negative impact on stream conditions (Hypothesis 1). Further, the inverse relationship between the aggregation of forest and B-IBI indicates that an intact and mature forest within a watershed positively influences stream conditions (Hypothesis 2). However, because of the high correlation between the aggregation and hydrological connectivity of paved land and amount of impervious surface in the basin we cannot reject the hypotheses that there is not significant relationship between basin level aggregation of paved land and B-IBI values (Hypothesis 1) and between basin hydrological connectivity of paved land and B-IBI values (Hypothesis 3) that is not already explained by the amount of TIA in the basin.

While there are multiple mechanisms operating simultaneously in urban basins and certainly this study cannot discriminate among the contributions of these multiple stressors, our results suggest the importance of investigating more explicitly patterns of urban development to better understand the relationships between urbanization and aquatic ecological conditions.

Our analysis of land use-land cover reveals that urbanizing landscapes are characterized by a complex pattern of intermixed high- and low-density built-up areas, showing that urban land cover and impervious surface cannot account for the difference that alternative development patterns may generate. We suggest that urban landscape stressors can best be described using a series of pattern metrics that describe spatially aggregated variables of land-use intensity and land-cover types (e.g., density of human population, road density, or amount of impervious surface) and spatial distributions and configuration of the landscape.

Since the 42 selected sub-basins represent a cross-section of varying levels and patterns of urbanization in the Puget lowland, the results are transferable to other urbanizing sub-basins of similar size and hydrogeology. The established relationships between urban pattern and ecological conditions however do not indicate a specific threshold of effects but do show that both the percentage impervious surface and its aggregation have a direct impact on stream ecological conditions. While this study provides an initial exploration of how development patterns influence ecological conditions, much remains to be explored. More research could be pursued to assess the relative ecological importance of local influences once watershed scale factors are controlled for. Furthermore an explicit exploration of the mechanisms by which patterns of urban development affect stream ecological conditions is necessary. This knowledge is critical in determining the processes that need to be maintained in order to ensure that ecosystem services can simultaneously support humans and other species.

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