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Twenty-five years of sprawl in the Seattle region: growth management responses and implications for conservation

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Abstract

To study the effects of growth management efforts on urban fringe areas in Washington State's Puget Sound region, USA, this study documents and quantifies transformations in land cover and land-use from 1974 to 1998 for a 474 km^2 study area east of Seattle. Geo-referenced aerial photographs (orthophotos) were digitized, then classified, to compare patch patterns (clustered versus dispersed vegetation, remnant versus planted vegetation), size, development type (single-family housing, multi-family housing, commercial) and percent vegetative cover between 1974 and 1998 images. Changes in interior forest habitat and amount of edge were also calculated. The study showed that suburban and exurban landscapes increased dramatically between 1974 and 1998 at the expense of rural and wildland areas. Settled lands became more contiguous while rural and wildland areas became more fragmented. Interior forest habitat in wildland areas decreased by 41%. Single-family housing was the primary cause of land conversion. Current growth management efforts prioritize increasing housing density within urban growth boundaries (UGBs), while limiting densities outside these boundaries. The study demonstrated that housing density has indeed increased within these boundaries, but at the same time, sprawling low-density housing in rural and wildland areas constituted 72% of total land developed within the study area. Therefore, policies to reduce the density of settlement outside urban centers, in part to protect ecological systems, may have unintended environmental consequences. This has implications for those urban areas, both in the United States and in other countries, considering growth management strategies.

Keywords: Edge; Forest conversion; Growth management policy; Habitat fragmentation; Landscape patterns; Low-density housing; Sprawl; Urban growth boundaries

1. Introduction

"Sprawl" is a relatively new pattern of human settlement characterized by a haphazard patchwork of low-density housing and commercial strip development created by and dependent on extensive automobile use (Ewing, 1997; Gillham, 2002). Sprawl typically moves away from existing settlement in a "leap-frog" pattern, as widely spaced developments initially occur several kilometers from the central business district and later become connected by infill development. In the early 20th century, urban populations in the United States were concentrated within cities, but by the 1960s, this pattern began to change. During the 1970s and 1980s, more than 95% of US population growth took place in suburban areas outside cities (Gillham, 2002). Today, in the US, more people live and work in suburbs than in cities. As a result, sprawl has emerged as the

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dominant development pattern throughout much of the US.

The scattered, low-density development characteristic of sprawl occupies far more land than does multi-storied and higher-density urban centers (Bullard et al., 2000), and has significant effects on the land and its resources. Consequently, the area covered by urban and suburban growth often increases faster than population growth. For example, in the Chicago metropolitan area, while the population grew by 38% from 1950 to 1990, developed land increased 124% (O'Meara, 1999). Sprawl has also been shown to have significantly higher economic and social costs than more compact developments, particularly with regard to transportation and other infrastructure costs (Benfield et al., 1999).

In the US, sprawl is converting forests, agricultural land, and wetlands into built environments beyond the edges of urbanizing areas (the "urban fringe") at an alarming and increasing pace (Gillham, 2002). Sprawl affects water supply, wildlife, habitat availability, and overall habitat quality (Matlack, 1993; Zuidema et al., 1996; McDonnell et al., 1997; McKinney, 2002). Sprawl, for example, is responsible for 51% of all wetland loss in the US (US Fish and Wildlife Service, 2000). Sprawl not only consumes natural habitats but also fragments, degrades, and isolates remaining natural areas (Marzluff and Restani, 1999; Marzluff, 2001). The sprawl landscape is unlike the original and is often dominated by non-native plantings. As a result, natural vegetation or protected areas in and adjacent to sprawl settlement may be more susceptible to invasion by non-native species and may quickly become dominated by such species (Zuidema et al., 1996; Cadenasso and Pickett, 2001; Marzluff, 2001).

The impacts of increased urbanization and sprawl development are also apparent in many regions worldwide (Vitousek et al., 1997; Marzluff, 2001; Alberti et al., 2003). Loss of agricultural land due to urban sprawl has been an issue for decades in The Netherlands, caused largely by construction of industrial and commercial facilities in urban fringe areas, as well as the desire for more living space (Valk, 2002)—ostensibly fueled by pursuit of the Dutch version of the "American dream" (Tjallingii, 2000). Urban sprawl is also the dominant feature of urbanization in Japan, particularly within commuting distance of major cities such as Tokyo, Osaka, and Nagoya (Sorensen, 1999). Sprawl is becoming an issue in Russia, although Moscow appears to be the only major metropolitan area affected thus far (Ioffe and Nefedova, 2001, 1998). Residential and recreational use of land around Moscow, primarily due to the construction of second summer homes ("dachas") and cottages, is leading to loss of commercial agricultural lands (Ioffe and Nefedova, 2001, 1998). The loss of forests, agricultural lands, and open space to urban sprawl is also an issue in Canada (Rothblatt, 1994), the United Kingdom (Breheny, 1995), and Israel (Razin, 1998).

Although there are many areas affected by sprawl, we selected King County, Washington, home to Seattle, as our study area. The population in King County is growing rapidly and is becoming more urban. In just 30 years (1970–2000), the county's population increased 44%, from 1.2 to 1.7 million, while the number of households increased by 72% (from 400,000 to 680,000; KCORPP, 2000a). This trend is expected to continue. For example, between 1995 and 2015, planners forecast an additional 150,000 households for the region, with a significant proportion of new construction expected along the urban fringe (KCORPP, 2000a). King County is therefore an appropriate site to study the extent and impacts of land conversion at an urban fringe.

Recognition of the costs of sprawl has prompted policy makers throughout the world to create various regulations and incentives to reduce it, including regulatory controls on pattern and density of development, establishing urban growth boundaries (UGBs), restricting new residential development in agricultural areas, establishing greenbelts, pacing new development to match development of new infrastructure, restricting the numbers of new residential permits issued, land preservation programs, and tax incentives (Porter, 1997; Razin, 1998; Tjallingii, 2000; Gillham, 2002). Management programs that attempt to balance growth while fulfilling economic, social, and environmental needs are often termed "smart growth" programs. Such programs may include a combination of the programs listed above or may focus on a single approach (Porter, 1997; Benfield et al., 1999; Gillham, 2002). Washington State, for example, has attempted to deal with the issue of sprawl through the use of urban growth boundaries established on a county-wide basis (KCORPP, 2000a).

Growth management efforts in King County, Washington, were first initiated by its 1964 comprehensive plan, however, serious efforts to deal with growth management issues began with the 1985 comprehensive plan (KCDPCD, 1985). The 1985 plan attempted to manage new growth while meeting economic needs and providing affordable housing, public facilities, and other services. The 1985 plan called for most new growth to occur in designated "urban" and "transitional" areas. Residential development in "rural" areas was still allowed, but at lower densities. For example, the density of residential development in rural areas was reduced from one dwelling unit per acre (0.4 ha) to 1 dwelling unit per 2.5–10 acres (1–4 ha) by the 1985 comprehensive plan (KCDPCD, 1985; Reitenbach, personal communication). The 1985 plan also established permanent forest and agricultural production districts where very little new residential development was allowed.

In 1990, Washington State promulgated the Growth Management Act (GMA; Chapter 36.70A RCW), which has a primary goal of minimizing land conversion and environmental impacts by concentrating growth in urban areas. Local jurisdictions, such as city and county governments, were required to work together to prepare comprehensive plans that balanced growth, economics, and land-use while providing affordable housing and other public services. Local jurisdictions were also required to designate specific long-term urban growth boundaries, based on population and economic growth projections through the year 2012. In 1992, King County and elected officials from cities within the county collaborated to produce county-wide planning policies, which provided the framework for implementing the goals of the GMA (KCORPP, 2002). That document also established UGBs throughout the county. In 1994, city and county officials produced a new comprehensive plan, which provided the legal framework for making land-use decisions in unincorporated sections of the county and adopted the UGBs set forth in the planning policies (KCORPP, 2001). In compliance with the GMA, local governments within the county also prepared new or revised existing subarea plans to implement county-wide growth management policies at the local level.

Washington's GMA, as well as King County's planning documents, all have specific goals and/or policies related to growth management such as encouraging development in urban areas, reducing the "inappropriate conversion of undeveloped land into sprawling, low-density development," conserving fish and wildlife habitat, and protecting and enhancing the environment (KCDPCD, 1985; KCORPP, 2001). It is not the intent of these plans to prohibit growth outside of urban areas, but instead to direct most new growth to the areas inside the UGBs (KCORPP, 2002). In King County, this was accomplished primarily by zoning. Urban areas were zoned for higher residential densities (at least 1–12 dwelling units per acre [0.4 ha]), while areas designated as "rural" were zoned for lower residential densities (generally 1 dwelling unit per 2.5–10 acres [1–4 ha]; KCORPP, 2001). In addition, the permanent forest and agriculture production districts established by the 1985 comprehensive plan were continued virtually unchanged in the 1994 plan and were also zoned for very low residential densities (1 dwelling unit per 10–80 acres [4–32 ha]; KCORPP, 2001). Thus, growth management in King County featured a two-pronged approach: urban growth boundaries were used to define the areas where most new growth was desired over a 20 year planning period, and a combination of low-density residential zoning and long-term designation of resource production lands were used to decrease the potential for new growth outside the UGBs.

The landscape-level effects of these growth management programs can be seen on Fig. 1. More than half of the county consists of natural or second growth forests, "protected" from unmanaged growth by designation as forest production areas, parks, open space, or wilderness. The Westernmost section of the county is highly urbanized. Designated rural areas provide a slower-developing transition or buffer zone between the UGBs and protected forest lands.

While these planning measures and others attempt to address the problem of sprawl, scientific research to quantify the specific patterns of sprawl over time has been limited. Truly basic questions are not only unanswered, but unasked. For example, what is the pattern of land conversion? How, specifically, did the landscape change? What are the patch patterns of development and remaining vegetation?

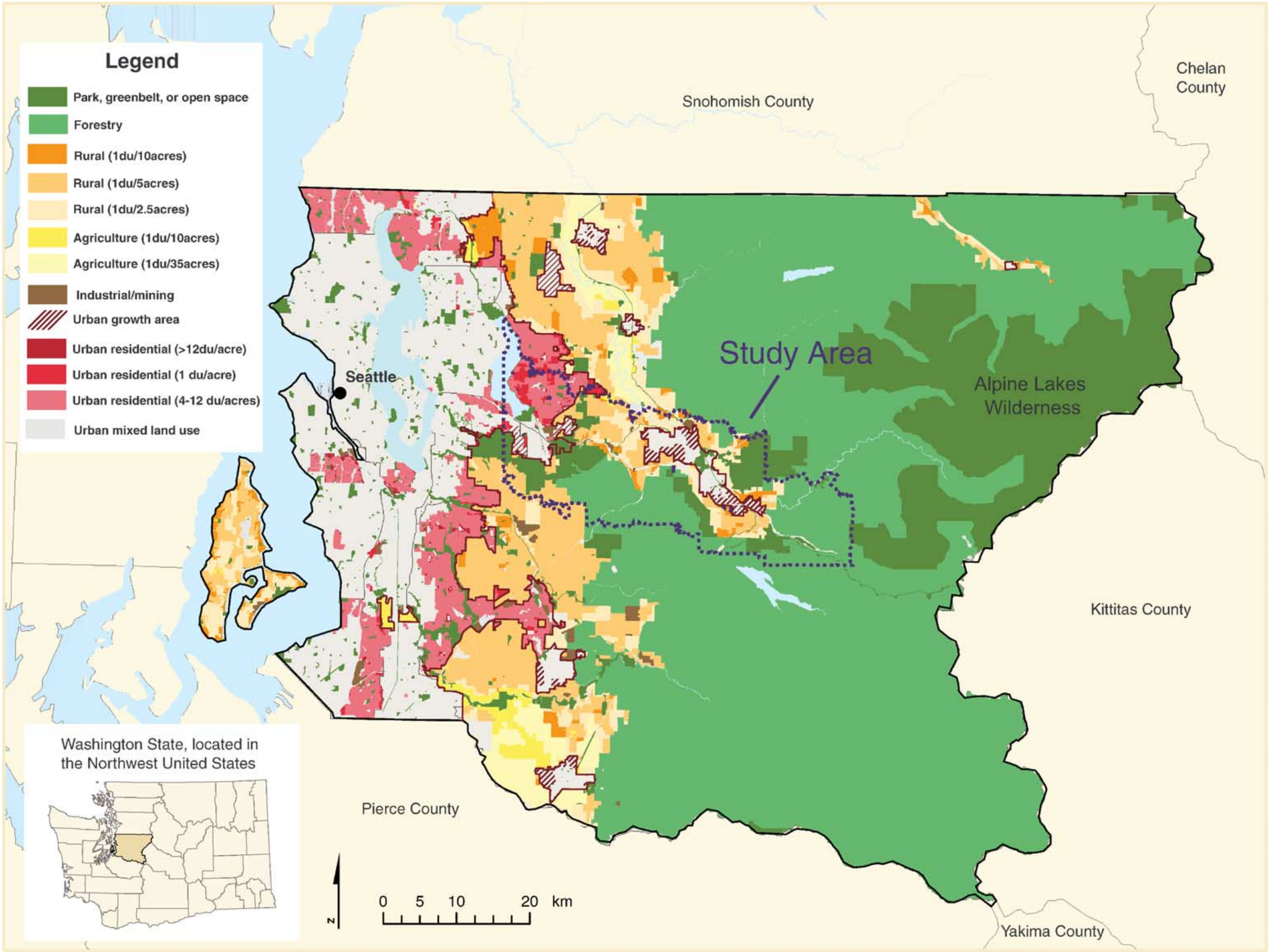

Fig. 1. Land-use and zoning in the study area and vicinity. The Interstate 90 highway runs West–east through the middle of the study area, which is about 15 km East of Seattle. Source: King County, 2002.

Seeking answers to these questions and others, an exploratory study was conducted to document and quantify transformations in land cover and land-use from 1974 to 1998 in a 474 km^2 section of the urban fringe in the Seattle, WA area (Fig. 1). The objectives of the study were to determine how sprawl has changed landscape composition, vegetative pattern and type of vegetation, primarily from a wildlife conservation perspective. The proximate causes of these changes such as growth management policies and the effects of housing density on wildlife habitat, were also explored.

2. Methods

2.1. Selection of study area

King County is geographically diverse, ranging in elevation from sea level in the west along Puget Sound, to about 2400 m in the Cascade mountains to the East. Urban development dominates the Western third of the county, but becomes less dense as one moves East from the Puget lowlands into the foothills of the Cascades. An area east of Seattle (Fig. 1) that spanned a gradient of landscape types, from suburban centers and less-developed rural/exurban lands to forested wildlands, was selected for study. The 474 km^2 study area extends 42 km from the Southeastern shores of Lake Sammamish to the town of North Bend. Northern and Southern boundaries are approximately 5 km North and South of interstate 90 (I-90). The study area encompasses cities that have designated UGBs as well as unincorporated land. However, because it includes I-90, the major East–West arterial, more development has occurred within the study area than is typical for most other portions of Eastern King County.

2.2. Development of geographic database

Aerial photography can document the built environment and its temporal changes (Wu and Yeh, 1997). For this study, geo-referenced black and white, summer-scene, aerial photographs (orthophotos) supplied by the Washington Department of Natural Resources (DNR) for 1974 and 1998 were analyzed to develop a digital record of land cover and land-use in the study area. The year 1998 was selected because it was the most recent data available when the project began. The year 1974 was the earliest year available at the same scale as the 1998 photos. Comparable scale photos were essential for precise comparison. However, the 1974 photos, unlike those for 1998, were only available in paper format. Thus, the 1974 orthophotos had to be scanned, then geo-referenced using ERDAS software (ERDAS, 2002), before analysis.

Using ESRI arc view 3.2 geographic information system (GIS) software, a five-member team manually digitized then classified homogenous patches (i.e. polygons) on each set of orthophotos. To aid in consistency, all polygons were classified based on the characteristics detectable at a scale of 1:14,000. Given the resolution of the orthophotos, 2 ha was considered the smallest consistently mappable unit. Arcview's patch analyst was used to aggregate polygons with similar classifications into patch types for analysis of patch size and calculation of other landscape metrics. GIS data layers provided by King County (King County, 2002) were used to investigate land-uses and growth management policies in the study area.

2.3. Classification of digitized polygons

Digitized polygons were coded for specific land cover and land-use characteristics, and for types and patterns of vegetation, using a classification system developed to meet the specific needs of this study. This information was then used to quantify land conversion and to analyze specific patterns (e.g. clustered versus dispersed vegetation, remnant versus planted vegetation), patch size, development type (e.g. single-family or multi-family housing, commercial/industrial), and habitat type (forested versus non-forested vegetation).

Each polygon was classified based on a hierarchical system (Table 1). First, polygons were viewed in a 1 km^2 setting to determine the landscape-level context for each polygon. Five categories were used to describe the dominant landscape: urban, suburban, rural, exurban, and wildland. Because of confusion in the literature over their exact meanings (McIntyre et al., 2000; Marzluff et al., 2001), they were explicitly defined for this study (Table 2). A photographic example of the dominant landscapes defined in Table 2 is shown on Fig. 2. Note that no areas within the study area met the definition of "urban" as defined for this

Table 1
Hierarchical land classification system

Dominant landscape (level 1)	Suburban, rural, or exurban		Wildland	
Dominant land cover or land-use (level 2)				
Bare soil	Unpaved gravel roads, or unpaved gravel lots		Unpaved gravel roads, or Unpaved gravel lots	
Paved	Multi-lane/interstate road, or paved road, or paved lot		Multi-lane/interstate road, or paved road, or paved lot	
Unknown development	(1974 only. No subcategories)		(1974 only. No subcategories)	
Single-family residential, or multi-family residential, or commercial/industrial	<25% vegetation coverage, or 25–75% vegetation coverage, or >75% vegetation coverage. Majority clustered vegetation, or majority dispersed vegetation. Majority remnant vegetation, or majority planted vegetation		(Single-family, multi-family, and commercial/industrial designations not applicable to wildland areas. See "settlement.")	
Settlement	("Settlement" used only for wildland areas)		Residential only, or Residential/agriculture	
Forested vegetation, or forest production area	1998 subcategories	1974 subcategories	1998 subcategories	1974 subcategories
	Clearcut, or shrub growth/clearcut, or treed vegetation	Treed vegetation, or clearcut/shrubs	Clearcut, or shrub growth/clearcut, or treed vegetation	Treed vegetation, or clearcut/shrubs
Non-forest vegetation	1998 subcategories	1974 subcategories	1998 subcategories	1974 subcategories
	Grasses, or shrubs, or mixed grass/shrub/power corridor -or- Lawns: recreational lawns, or golf course, or other lawns -or- Agriculture: croplands, or orchards, or uncultivated fields/pastures	Agriculture, or other non-forested vegetation	grasses, or shrubs, or mixed grass/shrub/ power corridor -or- Lawns: recreational lawns golf course other lawns -or- Agriculture: croplands, or orchards, or uncultivated fields/pastures	Agriculture, or other non-forested vegetation
Water-related features	River, or lake, or possible wetlands		River, or lake, or possible wetlands	
Resource use/extraction	("Resource use/extraction" used only for wildland areas.)		Logging, or mining, or energy	

Polygons were classified by "dominant landscape", then by "dominant land cover or land-use". Polygons were further described using the categories below to each level 2 designation. For example, an area of single-family homes in a suburban area might be classified as: suburban, single-family residential, <25% vegetation coverage, majority dispersed vegetation, majority planted vegetation. An agricultural area might be classified as: rural, non-forest vegetation, agriculture, croplands.

Table 2
Definitions of dominant landscape categories

1. *Urban*: Buildings cover the majority of land. Building density is high and includes multi-family housing, multi-storied buildings, commerce, and industry. High-density single-family housing on relatively small lots (<0.2 ha) is also common. No urban areas were observed in the study
2. *Suburban*: Building density is moderate and lawns and other vegetation are often readily apparent. Lawns and gardens are generally more extensive than within urban areas. Single-family housing predominates on small to moderately-sized lots (0.1–1.0 ha). Multi-family housing, basic services, and light industry are scattered throughout. Structures over two stories tall are uncommon
3. *Rural*: Building density is relatively low and surrounded by agricultural lands. Settlement is sparse, primarily single-family housing on moderate to large lots (0.5–20 ha). For rural lands, we used 30% rather than 50% as the dominant landscape minimum because rural areas tend to be long and narrow in shape. Note that the above definition of rural differs from that of King County's, which define rural lands as any area outside of the urban growth boundaries (UGBs) that are not designated as agriculture or forest production zones (see Fig. 1)
4. *Exurban*: Building density is relatively low and surrounded by natural vegetation (forests). Average lot sizes are often smaller than rural (0.2–20 ha). Limited amounts of commercial agriculture may be present, but it does not dominate the matrix. Exurban development is largely single-family housing carved out of a forest matrix
5. *Wildlands*: Unsettled, primarily forested, lands that may occasionally include isolated dwellings

To determine dominant landscapes, buildings in each polygon were viewed within a 1 km^2 context and assigned to one of the five categories listed below. At least 50% of the 1 km^2 area was required for a polygon to be labeled a particular dominant landscape. Modified from Marzluff et al., 2001.

study. Also note that "wildland" is not used in the traditional sense in this study, but is used to denote large tracts (>0.5 km^2) of forest lands, with or without extremely light settlement. In this case, wildlands include privately-owned managed or unmanaged forests and government-owned parks, forest reserves, and wilderness.

Once the dominant landscape was determined, a polygon was then evaluated to determine the dominant land cover at the patch scale (level 2). The level 2 classifications functionally quantify land cover, but sometimes used differences in land-use to do so. For example, polygons were classified by different types of development (single-family or multi-family residential development or commercial development) rather than by simply defining land cover as "developed," (i.e. a mixture of impervious surfaces and anthropogenic structures). These distinctions permitted the quantification of a fine level of conservation-relevant changes in land cover.

Each polygon was further evaluated to determine the specific characteristics of land cover (level 3). For example, areas with residential or commercial/industrial development, were classified by the amount of vegetative cover (e.g., single-family residential settlement with <25% vegetation coverage 25–75% coverage, or >75% coverage). These metrics are important when assessing the value of the area as wildlife habitat. Undeveloped areas with forested and non-forested vegetation were classified by vegetation type (e.g., clearcut/shrubs, treed vegetation, or grass). Undeveloped areas in non-vegetated patches that were obviously not clearcuts (e.g., bare soil, paved) were classified by the nature of the land surface (e.g. paved or unpaved roads or lots; Table 1).

When possible, the specifics of land cover such as vegetation type and pattern were further described for each polygon. For example, polygons dominated by residential and commercial/industrial development were further classified as having clustered or dispersed vegetation and remnant or planted vegetation (Table 1). Remnant vegetation consists of the natural vegetation left after development while planted vegetation consists mainly of lawns and landscape plantings.Classification of the 1974 orthophotos differed slightly from classifications used for 1998. The classification system was initially developed based on the detail we believed could be accurately identified on the 1998 orthophotos. For example, at the onset of the project we believed that we could accurately distinguish between different types (coniferous, deciduous or mixed forest), ages (young versus mature), and complexity (simple versus complex) of forest vegetation on the 1998 orthophotos. However, the resolution was lower for the 1974 photos and differences between forest types less clear. As a result, the

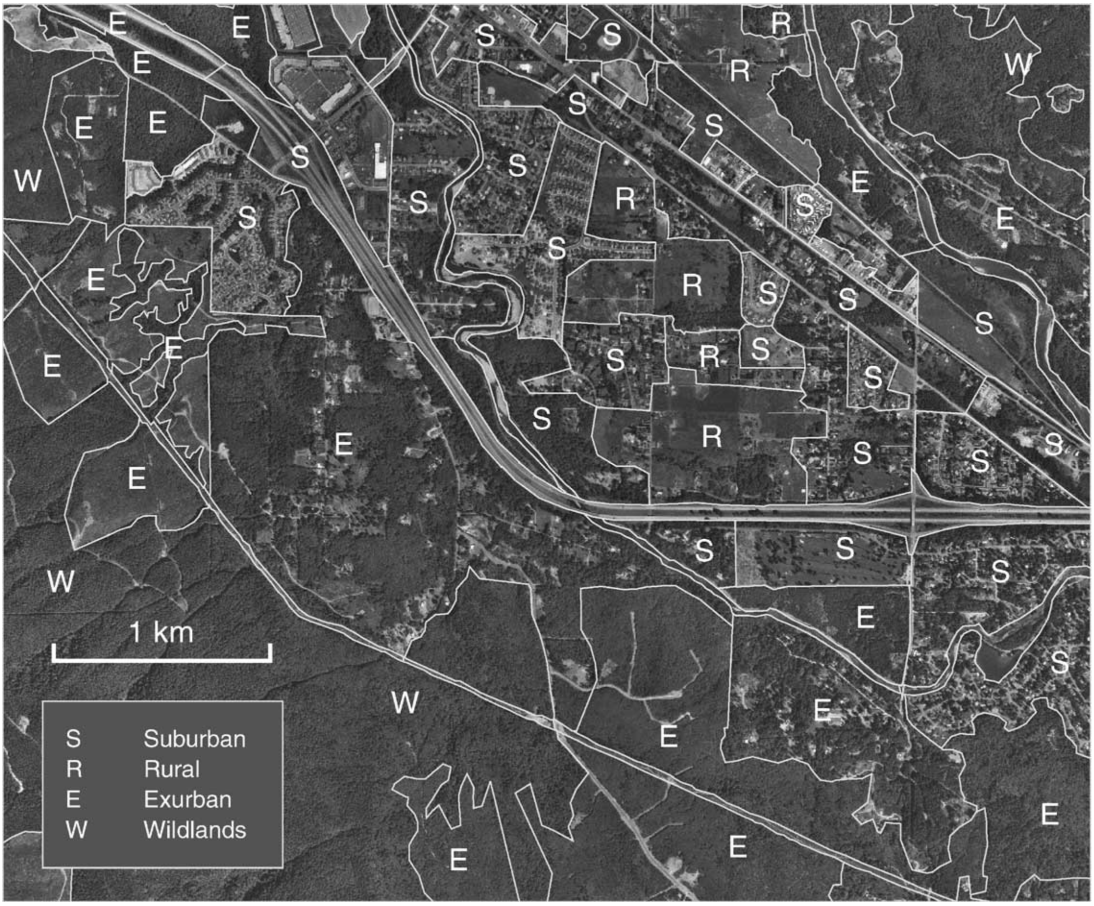

Fig. 2. A portion of the 1998 orthophoto image illustrating dominant landscape types.

number of categories used to classify forest vegetation on the 1974 photos had to be reduced from the twelve classifications initially used for the 1998 image, to two. The lower resolution of the 1974 image also affected the ability to accurately identify different types of development. Thus, a new classification category called "unknown development" (level 2) was added for the 1974 image.

At each classification level, polygons drawn on the orthophotos were classified based on the feature that comprised the greatest proportion of the polygon's area. All polygons were drawn to be as homogeneous as possible. However, some polygons contained more than one fine-scale land-use/cover type or vegetation pattern/type (see, for example, the polygons shown on Fig. 2). When this occurred, only the land-use/cover type or vegetation pattern covering the greatest portion of the polygon was recorded. For example, a polygon in a suburban landscape that encompassed a homogeneous area of single-family residential development would also contain paved roads. Because the residential development was the dominant feature, this polygon was classified as "suburban, single-family residential settlement" rather than as "suburban, paved" (see Table 1). The paved roads within the development were considered apart of the overall pattern of development, rather than the dominant feature. This same polygon probably had both remnant and planted vegetation. If remnant vegetation comprised more than 50% of the total vegetation, the polygon was classified as having "remnant vegetation" at the finest level of classification.

At the start of this project, rules for digitizing and classifying polygons were established to ensure consistency in classification, such as when to include roads within a polygon versus when to make roads their own polygon, or how to distinguish “bare soil” from a recent “clearcut.” To ensure accuracy and consistency in interpreting the orthophotos, a training session was held in the study area to jointly practice the assignment of classification codes.

Periodic ground-truthing was used to verify the accuracy of assigned classification codes (for the 1998 image) and to resolve questions and concerns that arose during the digitizing process. When inconsistencies were discovered, classification codes were modified to reflect actual conditions. Approximately 25% of the study area was ground-truthed during the classification process.

Questions and concerns regarding the 1974 orthophotos were more difficult to deal with. Questionable areas were compared to the 1998 image for clarification. For example, a fuzzy area on the 1974 orthophoto that appeared to be devoid of vegetation and possibly developed might show up as a well-established forest stand on the 1998 image, indicating that it was most likely a clearcut in 1974. Where questions could not be resolved, the polygon was classified as unknown development.

The consistency of codes assigned during the classification process was tested partway through the digitizing process. Three of the five digitizers did 40 sample trials to assess the team’s consistency. There were some inconsistencies. For example, dominant landscape (level 1) was inconsistently classified 18% of the time and land-use/cover (level 2) was inconsistently classified 5% of the time. To correct this, the entire team reviewed the definitions for dominant landscape (Table 2) and rules for digitizing. Each person then reviewed their portion of the study area and made changes as needed. In sections of the orthophotos where classification was difficult, team members worked together. Polygons on the 1998 image that were difficult to classify were later ground-truthed.

Consistency tests also showed that fine-scale distinctions for forest vegetation (e.g., deciduous versus coniferous forest, various forest ages) were inconsistently classified 23% of the time. Ground-truthing also showed that forest vegetation was inaccurately classified much of the time. As a result, the fine-scale distinctions for forests initially used for the 1998 period were combined into a few classifications (e.g. treed vegetation) prior to analysis (Table 1).

2.4. Calculating interior forest habitat and edge

Interior forest area and edge density were calculated for wildland landscapes using patch analyst (Rempel et al., 1999), assuming a buffer of 200 m to account for edge effects (Kremsater and Bunnell, 1999). Edge density, a measure of edge in relation to total area, was calculated by dividing total edge by total area. Interior forest area was also calculated for fragments of clustered/remnant forest in areas dominated by single-family housing in suburban, rural, and exurban landscapes. Using 200 m for the extent of edge effects, each patch of vegetation classified as clustered/remnant (>75% vegetative cover) in a polygon dominated by single-family housing was measured using arc view’s measurement tool to determine if the fragment had any area that was >200 m from settlement.

2.5. Patch analysis

The distribution of single-family housing and vegetative cover between the two study years was compared using a chi-square (χ^2) goodness-of-fit test. The number of patches of single-family housing or vegetative cover class (>25, 25–75, and >75%) were compared among dominant landscape classes (suburban, rural, exurban), also using the chi-square test. Mean patch size for each class of dominant landscape was also compared between study years using an independent samples *t*-test. Because the variance increased with the mean, all patch data was log-transformed prior to analysis (Zar, 1999).

2.6. Assessing the effects of changing policies

Growth management policies governing land-use and development in the study area changed significantly during the study period. Such policy changes can result in a noticeable change in housing development patterns around the time the new programs are implemented. Changes in patterns often start before new policies are enacted. For example, in the years just prior to adoption of the King County's 1985 comprehensive plan, there was a rush to subdivide larger parcels to "grandfather in" smaller parcels before lot sizes for buildable parcels increased (Reitenbach, Personal Communication). The effects of "grandfathering" could continue for up to several years after a new policy is enacted.

While the analysis of intermediate orthophotos (between 1974 and 1998) could reveal changes in land development patterns resulting from policy changes, it was unclear which years should be investigated. In addition, orthophotos were not available for many of the intervening years. Thus, external data sources were deemed superior than additional photo interpretation for determining the effects of these changes on the distribution of housing within the study area. Residential housing parcel data from King County (2002), which provides information about permits issued for construction of single-family residences county-wide, was analyzed for number of permits and amount of land developed on a year-by-year basis to look for changes in the pattern of residential land development, both inside and outside UGBs.

3. Results

3.1. Amount and pattern of change

Suburban and exurban landscapes increased between 1974 and 1998 (Fig. 3). In 1974, suburban and exurban lands together comprised just 8% of the study area, but by 1998 they covered almost a third. Suburban land increased by 756% and exurban land by 193% (Table 3). At the same time, rural lands decreased by 65% and wildlands by about 19%. Considering that in 1974 wildlands accounted for about 75% of the study area, this 19% decrease represents a substantial area (about 68 km^2). Together, the reduction of rural and wildland areas represent the conversion of 23% of the study area (about 108 km^2) from natural resource and agricultural production lands to residential and commercial development. Land that was suburban in 1974 generally remained suburban in 1998 (Table 4). However, only 19% of lands classified as rural in 1974 remained rural in 1998. Sixty-one percent of rural lands in 1974 became suburban by 1998, and 18% became exurban. Similarly, 19% of suburban lands and 17% of wildlands became exurban by 1998.

Settled lands became more contiguous during the 24-year study period, while fragmentation increased elsewhere (Fig. 4, Table 3). Mean patch size of suburban and exurban lands increased by 453% and 268%, respectively. This constitutes infilling between Seattle and the once-isolated fringe communities of Issaquah, Snoqualmie, and North Bend (Fig. 3). At the same time, mean patch size for rural and wildlands decreased, indicating increased fragmentation (Figs. 4 and 5). In addition to large differences in mean patch size between 1974 and 1998 for all landscape categories, there was also a large variance in patch size

Table 3
Patch size of dominant landscape categories

Category	Number of patches		Total area (ha)			Mean patch size (ha)						
	1974	1998	1974	1998	Percent change (%)	1974	Standard error (1974)	1998	Standard error (1998)	Percent change (%)	t	P
Suburban	9	14	668	5720	+756	74	43	409	319	+453	−1.121	0.275
Rural	74	34	6181	2176	−65	84	45	64	21	−24	−1.543	0.126
Exurban	77	62	3102	9090	193	40	19	147	74	+268	−2.835	0.005
Wildland	42	48	35437	28687	−19	844	711	598	405	−29	0.574	0.568
Water	–	–	1995	1730	–	–	–	–	–	–	–	–
Total			47383	47403								

A patch is defined as a contiguous area of homogeneous classification. Total patch size is the total area of a given landscape category and average patch size is the average based on total area divided by the total number of patches for a given landscape category for a given year. Percent change is based on the percent increase or decrease in area from 1974 to 1998. Tests of change in mean patch size are based on log-transformed data. Note that total areas of water features vary for each study year due to differences in digitizing their boundaries.

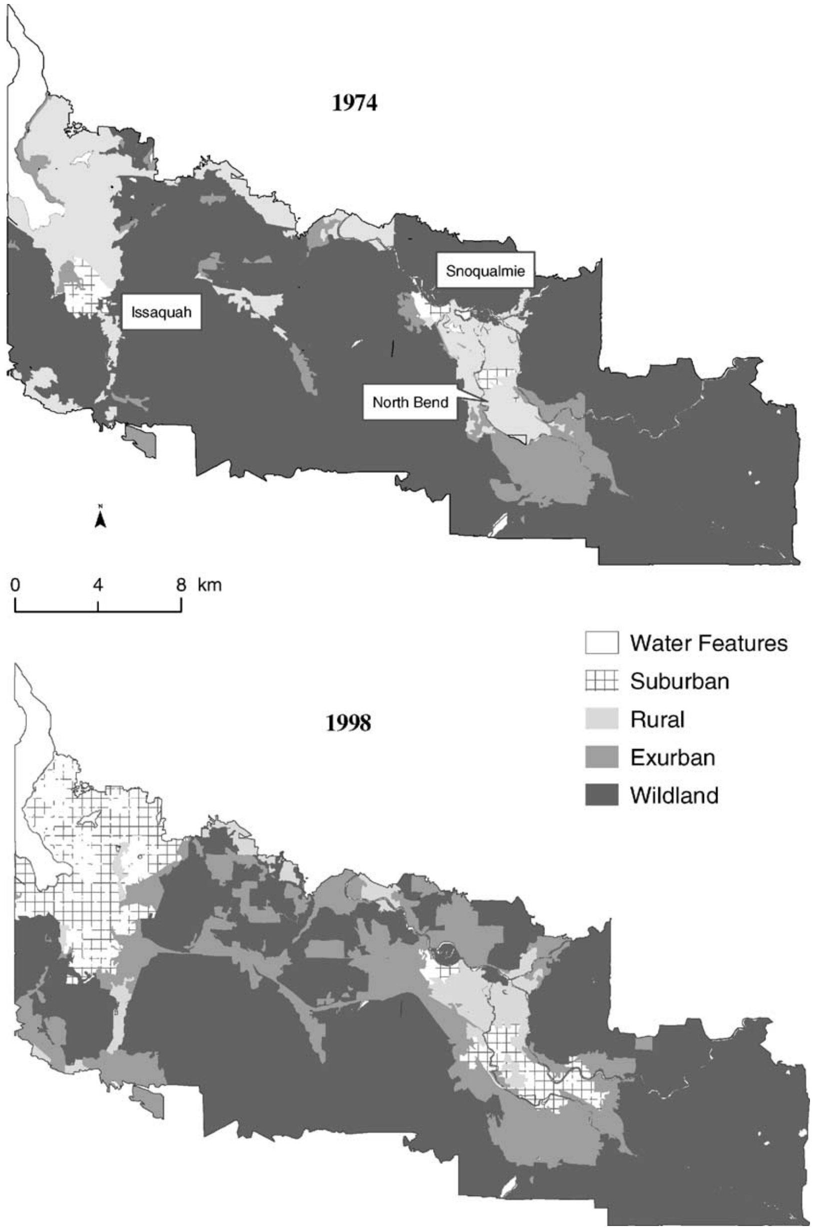

Fig. 3. Landscape configuration in 1974 and 1998. Note how suburban areas are expanding in a relatively continuous pattern replacing primarily rural areas. Exurban lands, meanwhile, show a more dispersed pattern and replace primarily wildland areas. Note that "wildland" is not used in the traditional sense, but instead denotes wild forests and forest production lands with extremely light settlement. Three cities shown in boxes (Snoqualmie, Issaquah, North Bend) are also included.

in 1998. Thus, only the increase in exurban patch size was statistically significant (Table 3).

Interior forest habitat in wildland areas, calculated assuming edge effects extend 200 m into wildlands from the other dominant landscape categories, decreased from 29,721 ha in 1974 to 17,679 ha in 1998, a loss of 41%. The number of wildland patches with some interior forest increased from 11 to 17, but the

Table 4
Percent change in dominant landscape from 1974 to 1998

Dominant landscape 1974	Dominant landscape 1998	Land area changed (ha)	Percent change from 1974 to 1998
Suburban	Suburban	661[a]	92
Suburban	Rural	4	1
Suburban	Exurban	47	7
Suburban	Wildlands	5	1
Rural	Suburban	3304	54
Rural	Rural	1780[a]	29
Rural	Exurban	880	14
Rural	Wildlands	1873	
Exurban	Suburban	688	22
Exurban	Rural	16	1
Exurban	Exurban	2373[a]	77
Exurban	Wildlands	21	1
Wildlands	Suburban	1054	3
Wildlands	Rural	240	1
Wildlands	Exurban	5733	16
Wildlands	Wildlands	28340[a]	80
Total		45282	

[a] Note that each category shows the amount of land that did not change. Note also that water features are excluded from this analysis.

average size of these areas declined by 61%, from 2701 to 1040 ha. Total edge (measured as the length of interface between wildland and other dominant landscape categories) decreased by 29%, from 913 to 644 km. This decrease in edge reflects the overall decrease in size of core areas. Edge density, a measure of edge in relation to total area, increased from 30 m/ha in 1974 to 36 m/ha in 1998.

In 1998, the amount of vegetative cover within single-family residential areas varied significantly ($\chi^2 = 45.3$, d.f. $= 4$, $P < 0.05$). Not surprisingly, the amount of vegetative cover within single-family housing developments was higher in rural and exurban areas than in suburban areas (Table 5). Eighty percent of the area covered by rural single-family housing and 92% in exurban single-family housing areas had >75% vegetative cover, but only 36% of suburban single-family residential areas had that much vegetation. In contrast, less than 5% of rural and exurban single-family residential areas had <25% vegetative cover, compared to 24% of suburban residential areas (Table 5).

Table 5
Vegetation cover in single-family housing developments, 1998

Category	<25%		25–75%		>75%	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Suburban	678.9	24	1090.7	39	1012.2	36
Rural	15.5	4	66.7	16	332.5	80
Exurban	15.5	<1	341.9	7	4422.5	92
Total	709.9	9	1499.3	19	5767.2	72

Single-family housing in rural and exurban areas are highly vegetated (>75%), while those in surburban areas have a mix of low (<25%), medium (25–75%) and high (>75%) levels of vegetation.

Vegetation in single-family housing developments was highly fragmented and the remaining fragments were frequently isolated with little connectivity (Fig. 5). In general, vegetation across all patches dominated by single-family development was dispersed (76%) rather than clustered (24%). In suburban and rural lands, much of the vegetation was planted (42 and 57%, respectively), not remnant. However, in exurban lands, remnant vegetation was dominant in 94% of all housing developments. Some developments had substantial fragments of clustered/remnant vegetation (Table 6). However, these fragments were mostly elongated (rather than compact), with a high edge/interior ratio. Even when adjacent fragments in areas dominated by single-family housing could be combined to form large patches, no patches had any area >200 m from the edge, and only one patch contained any area at a distance >100 m from an edge.

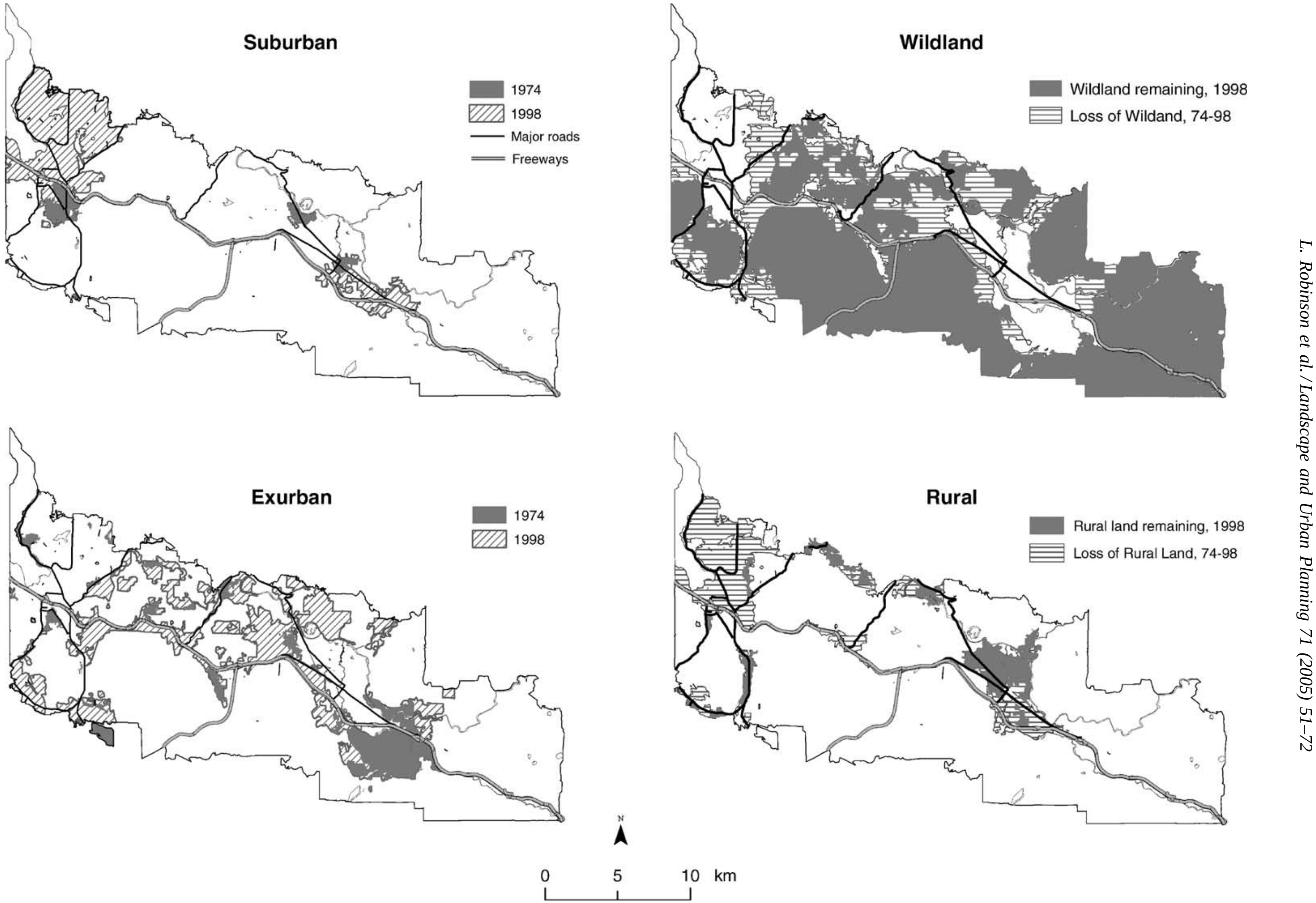

Fig. 4. Changes within each category of dominant landscape, 1974–1998. Each map shows change in dominant landscape (suburban, exurban, rural, and wildland) from 1974–1998. Note that suburban and exurban areas are increasing over time while rural and wildland (wild forests and forest production lands with light settlement) are decreasing. These are the same data contained in Fig. 2, but presented here to clearly show changes within each type of landscape.

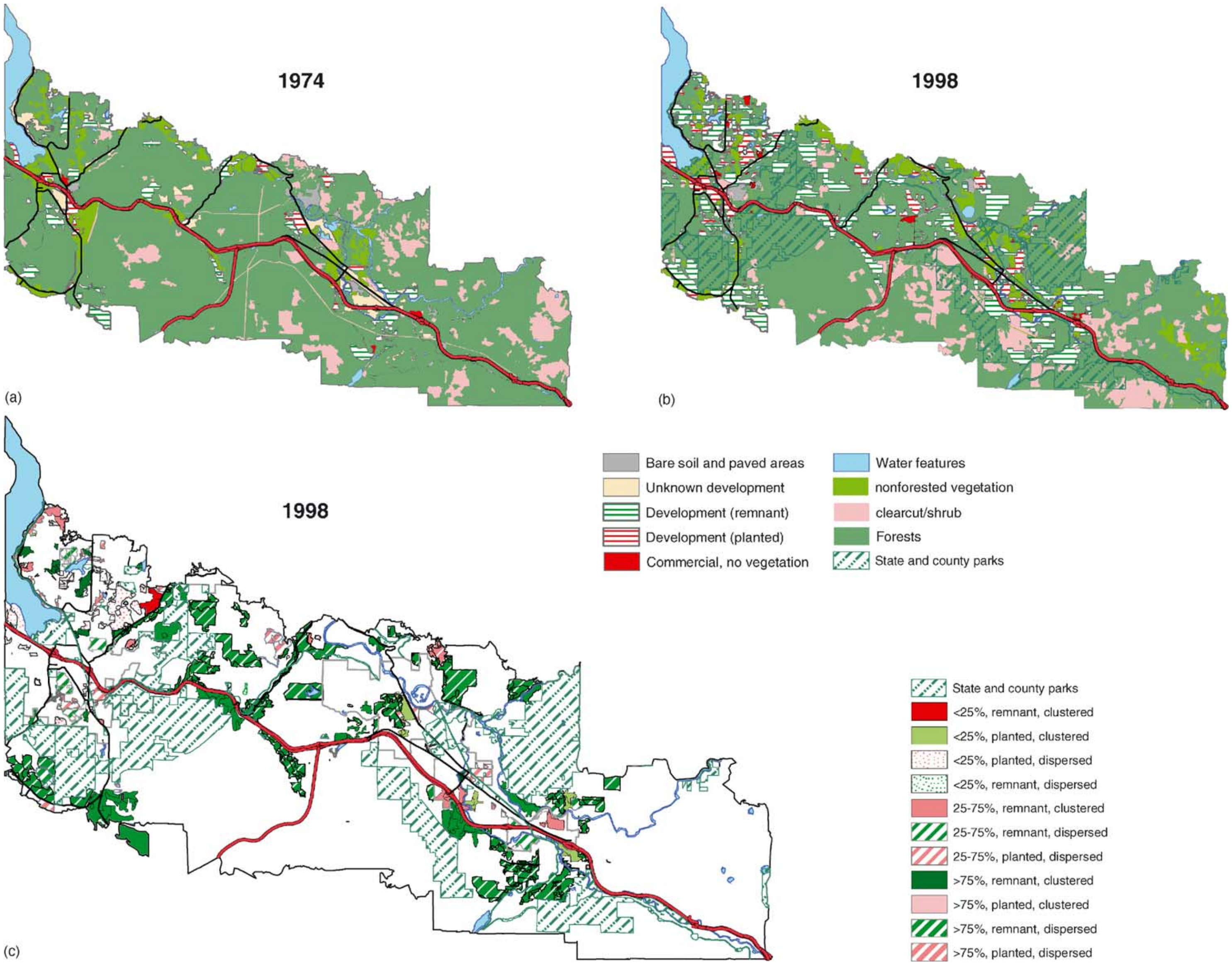

Fig. 5. Distribution of vegetation, 1974 and 1998; (a) and (b) show changes in vegetative cover; (c) shows vegetation patterns in single-family housing for 1998. No parks are shown for 1974.

Table 6
Total area with clustered/remnant vegetation

Category	<25% vegetation	25–75% vegetation	>75% vegetation	Total
Suburban area (ha)	70.2 (1)	214.1 (5)	173.3 (8)	457.6 (14)
Percent of total (%)	4	12	10	26
Rural area (ha)	0	30.1 (1)	18.3 (1)	48.4 (2)
Percent of total (%)	0	2	1	3
Exurban area (ha)	0	109.6 (3)	1137.4 (17)	1247.0 (20)
Percent of total (%)	0	6	65	71
Total Area (ha)	70.2 (1)	353.8 (9)	1329.0 (26)	1753 (36)
Percent of total (%)	4	20	76	100

Areas are totals by dominant landscape categories. Numbers in parentheses are number of patches.

There were approximately 271 more hectare of surface water in the study area in 1974 than in 1998. About 112 ha of the difference are due to the loss of surface water bodies to filling and development along shorelines. For example, three areas east of Snoqualmie that total about 60 ha were ponds in 1974, but agricultural fields in 1998 (Fig. 5). The presence of these agricultural fields in 1998 was verified by ground-truthing. The remainder of the difference (159 ha; 0.3% of the study area) appeared to be due to slight differences in digitizing rivers and lakes in the two study years. Because the 1998 image had a much higher resolution than the 1974 image, the shorelines of rivers and lakes were digitized much more tightly and accurately than for 1974. In general, polygons drawn for rivers and lakes were broader for 1974 than for 1998.

3.2. Expansion of low-density, single-family housing

Single-family housing was a primary cause of land conversion. Expansion of single-family housing (Fig. 6) closely resembles the overall pattern of land conversion (Figs. 3 and 4). There were significantly more patches of single-family housing in suburban and exurban areas in 1998 than in 1974 ($\chi^2 = 44.72$, d.f. $= 3$, $P < 0.001$), while the number of patches of single-family housing in areas now classified as rural and wildland remained relatively constant. However, most single-family development since 1974 has taken place in former wildland areas that are now classified as exurban. Conversion to commercial development was more frequent in already settled areas.

Total land developed for residential housing and commercial uses within the study area increased by 134%, from 3842 ha in 1974 to 8994 ha in 1998. In each study year, about 88% (3380 and 7976 ha, respectively) of developed land consisted of single-family housing. The percent of land devoted to commercial development also stayed relatively constant (12 and 10%, or 463 and 895 ha, respectively). No multi-family housing was observed in 1974, and only 1.4% (123 ha) of all developed land in the study area was classified as multi-family in 1998. It is important to note, however, that 1108 ha of developed areas were classified as “unknown development” in 1974 due to poor image resolution (Fig. 6). Comparison of these unknown areas to the same locations in 1998 showed that they were most likely to have been either single-family housing in 1974 or clearcuts later developed for single-family housing. As a result, they were grouped with single-family housing during analysis of 1974 data. Because of this uncertainty, however, the amount of single-family housing is likely overstated in 1974 and multi-family and commercial development may be understated.

3.3. Relationship between development patterns and policy changes

There was considerable expansion of low-density single-family housing outside the UGBs between 1974 and 1998 (Fig. 6). Although some of the development outside the UGBs occurred before the UGBs were established in 1994, residential housing parcel data from King County (2002) showed that

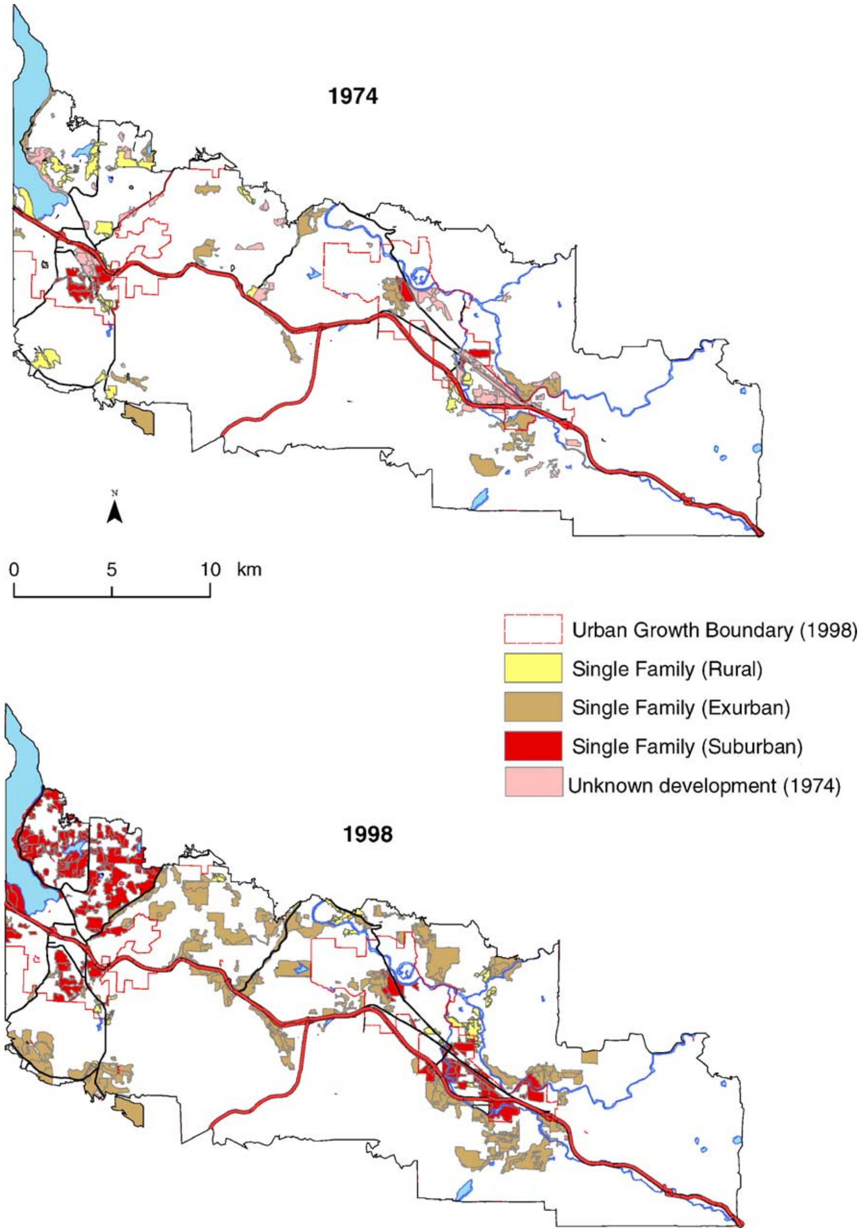

Fig. 6. Expansion of single-family housing within rural, exurban, and suburban landscapes, 1974–1998. For data analysis, unknown development is grouped with single-family housing in 1974.

a substantial portion occurred after the UGBs were established (Fig. 7; Table 7). However, based on a year-by-year analysis of residential building permits issued for the study area between 1974 and 2001, there was no clear pattern of development of rural areas related to implementation of either the 1985 or 1994 King County comprehensive plans. The correlation between study year and the number of residential building permits issued was weak (Spearman's rank correlation, $r = 0.13$, $n = 28$, $P = 0.51$).

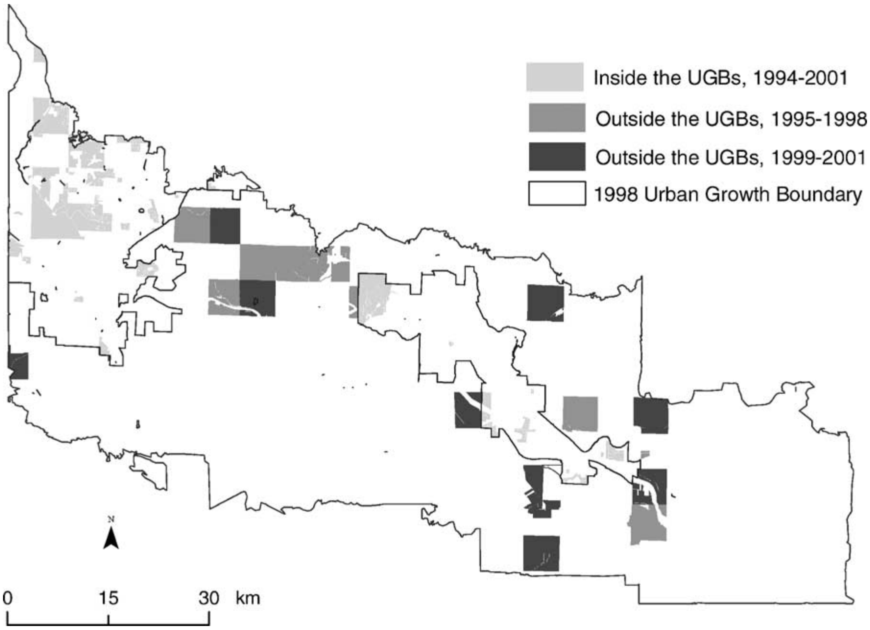

Fig. 7. Expansion, in land area, of residential housing outside of the urban growth boundaries (UGBs). Growth derived from King County residential parcel data, 1994–2001.

County parcel data showed that most of the residential building permits (77%) issued from 1995 to 1998 (following implementation of the 1994 comprehensive plan) were for parcels inside the UGBs, indicating that building density increased within existing urban areas. However, the increase in the percent of residential building permits issued within urban areas since establishment of the UGBs (1994) is rather slight (Table 7). From 1995 to 1998, 60% of land permitted for new residential development within the study area occurred outside the UGBs (Table 7). Thus, the total land area newly devoted to housing is much greater outside the urban growth boundaries, despite the relatively low number of residential building permits issued for those areas. These same trends continued through 2001 and are consistent with residential housing development county-wide. For example, parcel data for 1997 to 2001 show that county-wide, 14% of new residential building permits (5494) were issued for parcels outside UGBs, yet total land area developed for residential housing outside the UGBs was 61%. County-wide, a total of 14343 ha (61%) were committed to new residential construction outside UGBs, while 9084 ha (39%) of land was developed within UGBs from 1995 to 2001 (King County, 2002).

4. Discussion

4.1. Ecological effects of low-density development in King County

King County's growth management policies have targeted rural and wildland areas outside designated urban growth boundaries for low-density residential development, ostensibly to maintain rural character and protect the natural environment of these areas while still allowing some development to occur (KCORPP, 2000b). King County is not alone in using low-density development as a means to limit impacts to rural areas. Decreasing the density of residential housing, also known as "downzoning," has been used by many local governments, in an effort to maintain community character, create open space, and protect the environment (Gillham, 2002). However, as Gillham (2002) points out, downzoning is not necessarily an effective method for preserving rural

Table 7
Distribution of building permits and land committed to construction of residential housing within study area

Location	1974–1984				1985–1994				1995–1998				1999–2001			
	Land committed		Building permits		Land committed		Building permits		Land committed		Building permits		Land committed		Building permits	
	Area (ha)	%	Total	%	Area (ha)	%	Total	%	Area (ha)	%	Total	%	Area (ha)	%	Total	%
Inside UGB	1357	35	3000	62	1638	28	4901	72	1108	40	2152	77	323	15	1776	79
Outside UGB	2556	65	1874	38	4268	72	1836	28	1736	60	651	23	1825	85	474	21
Total	3913		4874		5906		6737		2884		2803		2148		2250	

Time periods relate to major changes in growth management policies (e.g. the 1985 and 1994 King County Comprehensive Plans), except for 1998–2000, which refers to the changes since the 1998 orthophoto. Data from King County (2002).

character or protecting the environment; additional houses are still constructed and undeveloped land is still subdivided into smaller parcels, all of which result in adverse environmental impacts, loss of open space, and increased traffic and infrastructure costs.

As shown by this study, the policy of low-density zoning has had unintended consequences. Despite the apparent increase in density of existing urban areas, this zoning policy has resulted in wide-spread, low-density single-family residential development outside the UGBs in the study area, resulting in substantial loss of rural areas and wildlands to suburban and exurban development. This has clearly had a major impact on landcover in the study area—converting, fragmenting, and isolating forest and rural lands. Native forest understories have been replaced with exotic, planted landscapes. The pattern of housing seen in exurban portions of the study area, dispersed throughout what were formerly rural areas and wildland, has noticeably reduced interior forest habitat. The few fragments of clustered/remnant vegetation present in patches dominated by single-family housing were too small to include interior habitat; just one patch had forest >100 m from its interface with developed land. Some patches without interior habitat were adjacent to parklands and working forests (Fig. 5), increasing the possibility of interior conditions. However, many of these working forests are themselves fragmented by roads and logging activities, which increase the potential for human impacts (Rochelle et al., 1999). For example, in his study of suburban forest fragments in Delaware, Matlack (1993) showed that sites adjacent to roads were significantly more affected by human activities than those away from vehicle access.

Fragmentation of once contiguous forests can potentially affect many sensitive species that require interior forest conditions. Species that would be negatively affected by this change in our area include the federally threatened Northern Spotted Owl (*Strix occidentalis*) and Marbled Murrelet (*Brachyramphus marmoratus*), neotropical migrant birds such as the Wilson's Warbler (*Wilsonia pusilla*), and sensitive resident species like Winter Wrens (*Troglodytes troglodytes*), spotted frogs (*Rana pretiosa*), Pacific giant salamanders (*Dicamptodon tenebrus*), dusky and Trowbridge shrews (*Sorex monticolus* and *S. trowbridgii*), and shrew-moles (*Neurotrichus gibbsii*).

Broadly applied low-density zoning policies need to be refined to reduce sprawl, fragmentation, and habitat loss. Rather than zoning all areas outside of UGBs for low-density residential development, King County and other local governments should consider zoning at least some of these areas at a variety of higher densities while limiting the overall number of dwelling units that could be constructed in a given area. In addition, some areas should also be zoned for clustered development. Clustering allows some land to be set aside as open space, helping to preserve rural character while reducing habitat loss, environmental impacts and infrastructure costs (Gillham, 2002). Within a given area, some parcels should be zoned for clustered development while others should be zoned for no development. In this model, the overall number of residential structures would remain the same, but much less land would be consumed. As an example, if rural residential lot sizes were reduced from 2–8 ha (5–20 acres) to 1 ha (2.5 acres; still a relatively large lot), and if these residential parcels were clustered, then a substantial amount of land would remain undeveloped and possibly even able to provide interior forest conditions. If this had been done in the study area, the amount of land consumed by the 1125 residential structures constructed outside UGBs between 1994 and 2001 would have been reduced from 8905 to 2813 acres, a reduction of 68%. This would have greatly decreased the fragmentation of forests and losses of interior forest documented by this study.

King County has taken some steps to encourage protection of significant habitats and other critical areas in rural and exurban areas, including buffering sensitive watercourses, creating interior forest reserves, protecting rare habitat elements (dead and downed trees, native understory, seeps, etc.), and maintaining key ecosystem processes (decay, natural disturbance regimes including fire, etc.). However, designation of long-term forest and agriculture production areas has had the most beneficial impact in terms of the broader landscape-level conservation of environmental resources in the county. As shown in Fig. 1, more than half the county has received these long-term designations; this has strongly limited the spatial extent of future growth. In these production areas, land has to remain in large parcels, the priority land-use is for agriculture or forest production, and there are strong limitations on development (King County, 1994). With these designations, the county has effectively created three development zones: urban growth areas, lower density rural areas, and forest and agriculture production areas (see Fig. 1). Thus, while we see sprawl occurring within the study area, the future extent of sprawl has been effectively limited by designation of the forest and agriculture production areas as well as the proximity of large state and federal land holdings.

This foresight by King County should not be underestimated. At present, more than 250,000 acres of King County's forest production lands are in private ownership (KCORPP, 2001), with the remainder consisting of large blocks of federal, state, or county-owned land. Most of the privately held lands are adjacent to the rural areas slated for low-density development. Given the amount of privately-owned forest production land, it is likely that some of these areas would have already been developed without these long-term designations, thereby increasing the extent of sprawl. Although little new residential construction is supposed to occur in these areas, they are already under pressure for a greater level of development (The Seattle Times, 2000).

4.2. Applicability and generalizability

The results from this study indicate that aerial photographs (orthophotos) are an accurate means to document and analyze land-use/land cover changes and patterns in urbanizing areas. When used with computer-based GIS programs, high-quality orthophotos provide a level of landscape detail not achievable with remote sensing. Aside from the scale resolution limit of about 7000:1, the primary limiting factor is the ability of classifiers to accurately and consistently identify the details shown on the photo. This can be overcome through the use of strict rules for digitizing and classifying, and training sessions. The classification system used to describe land cover/land-use in the study area can also be a limiting factor if the needs and objectives of the study are not well thought out before beginning the digitizing process. The need for constant communication between classifiers and the need for ground-truthing throughout the classification process became readily apparent during the course of this study. Periodic tests of consistency between classifiers are also necessary to ensure that the data generated are reliable.

With these measures in place, use of orthophotos, the classification system, and method are recommend for those researching the heterogeneous, dynamic landscapes found in urbanizing areas in other geographic regions. For example, using high-resolution orthophotos coupled with an appropriate classification system would add valuable ground-level detail to an analysis of land cover/land-use changes, such as the on-going studies being conducted in Russia using a combination of satellite imagery and historical maps (Milanova et al., 1999). Similarly, an orthophoto study could add detail to an analysis of the pattern of residential construction found in areas where government policies limit construction, such as in the "Green Heart" area of the Netherlands (Tjallingii, 2000).

The habitat fragmentation and loss of interior habitats documented by this study are generalizable to geographic areas throughout the world experiencing rapid growth and sprawling, low-density development. This is wide-spread throughout the Western US, where exurban and rural settlement is common throughout privately held lands (Hansen et al., 2002). Fragmentation of forests, open space, and agricultural lands is also a frequently-discussed impact in other countries including The Netherlands (Valk, 2002) and Japan (Sorensen, 1999). The spatial extent of low-density settlement is likely unique to each region and set by a combination of settlement policies. Washington State, for example, has strong growth management policies that have slowed moderate- to high-density settlement beyond county-defined UGBs. However, even such legally-mandated growth management appears unable to truly limit lower density settlement in privately-owned agricultural and forested lands beyond urban growth boundaries. For example, this study showed in that in King County, 61% of land committed for residential construction between 1995 and 2001 took place outside designated urban growth boundaries. Similarly, "compact city" policies that encourage construction of new residential development within existing urban centers, coupled with restrictive land development policies for the rural green heart area of The Netherlands, have not been entirely successful. Tjallingii (2000) noted that a substantial portion of new residential construction is still occurring within the restricted green heart area, including 43% of new housing between 1989 and 1994. In King County, local geology, land ownership, and zoning interact to stop settlement in high-elevation federal and state lands that are currently zoned for resource production and recreation. In other settings, lands reserved from settlement may not exist in proximity to sprawling urban centers and therefore more extensive low- to high-density settlement is likely depending on the existence of local growth management policies.

5. Conclusions

Policies encouraging dispersed, low-density development in rural and wildland areas have clear implications for planners and biologists. This paper showed that scattered, low-density housing consumes natural habitat, in much greater quantities than if housing were predominantly constructed at higher densities in more compact developments (Gillham, 2002). The unintended consequence—the increasing loss, fragmentation, and isolation of natural habitats—is the opposite of what these policies were intended to accomplish: conserve fish and wildlife habitat, protect and enhance the environment, while still allowing some residential development to take place (KCORPP, 2000b). The power of designating long-term natural resource and agriculture production areas, in combination with policies that encourage increased density of urban areas and limit growth in more rural areas, is also clearly indicated. Without these long-term designations, sprawling, low-density development would likely become more wide-spread throughout the county, increasing habitat fragmentation while decreasing the amount of interior habitat available to wildlife species. The designated forest and agriculture productions lands act as a barrier, effectively limiting the spread of new residential development away from urban areas.

As human populations become increasingly urban, without policy changes to control it, sprawl will become even more wide-spread than at present. In the year 2000, about 3 billion people (50% of the world's population) lived in urban areas and this figure is expected to reach 5 billion by 2025 (UNU/IAS, 2003). Countries enacting growth management policies to control sprawl should be wary of using low-density zoning to limit development in the more rural areas outside urban centers. As this study showed, using low-density zoning to restrict development may have unintended consequences and may in fact encourage sprawl.

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