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Ecological consequences of fragmentation and deforestation in an urban landscape: a case study

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Abstract Landscape change is an ongoing process even within established urban landscapes. Yet, analyses of fragmentation and deforestation have focused primarily on the conversion of non-urban to urban landscapes in rural landscapes and ignored urban landscapes. To determine the ecological effects of continued urbanization in urban landscapes, tree-covered patches were mapped in the Gwynns Falls watershed (17158.6 ha) in Maryland for 1994 and 1999 to document fragmentation, deforestation, and reforestation. The watershed was divided into lower (urban core), middle (older suburbs), and upper (recent suburbs) subsections. Over the entire watershed a net of 264.5 of 4855.5 ha of tree-covered patches were converted to urban land use—125 new tree-covered patches were added through fragmentation, 4 were added through reforestation, 43 were lost through deforestation, and 7 were combined with an adjacent patch. In addition, 180 patches were reduced in size. In the urban core, deforestation continued with conversion to commercial land use. Because of the lack of vegetation, commercial land uses are problematic for both species conservation and derived ecosystem benefits. In the lower subsection, shape complexity increased for tree-covered patches less than 10 ha. Changes in shape resulted from canopy expansion, planted materials, and reforestation of vacant sites. In the middle and upper subsections, the shape index value for tree-covered patches decreased, indicating simplification. Density analyses of the subsections showed no change with respect to patch densities but pointed out the importance of small patches (≤5 ha) as "stepping stone" to link large patches (e.g., >100 ha).

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Using an urban forest effect model, we estimated, for the entire watershed, total carbon loss and pollution removal, from 1994 to 1999, to be 14,235,889.2 kg and 13,011.4 kg, respectively due to urban land-use conversions.

Keywords Deforestation · Fragmentation · Connectivity · Ecosystem benefits

Introduction

Fragmentation and deforestation of natural habitats by human activities are one of the major factors contributing to the decline of biodiversity locally, regionally and globally. Fragmentation and deforestation reduce critical habitat, alter existing habitat, increase the dispersal distances between habitats for species, and increase species isolation (Saunders et al. 1991). In fact, dispersal becomes increasingly problematic as the landscape becomes more inhospitable and restricts animal movement.

Regional analyses of fragmentation have reported changes across broad land-use categories (e.g., Anderson Level 1 (Anderson et al. 1976))—urban, agriculture, forest, and transportation (e.g., Sharpe et al. 1986; e.g., Iverson 1988; Turner 1990; Zipperer et al. 1990). These analyses often do not capture the spatial complexity of land covers/uses within a category. For example, in an Anderson Level II classification, urban land use can be divided into residential, commercial, institutional, vacant, park, and transportation (Anderson et al. 1976). Accounting for this complexity is important for species conservation and management. An analysis of avian diversity by land use revealed shifts in composition from native cover to extensive urban cover (Blair 1996). To effectively manage avian diversity within an urban landscape, it is important to know how habitats change by land use (Marzluff and Ewing 2001). Unfortunately, we know little about habitat change and patch dynamics in urban landscapes.

Fragmentation and deforestation also affects the availability and quality of the goods and services humans derive from the ecosystem. Examples include reduced air and water quality, carbon sequestration, pollution removal, recreational opportunities, noise reduction, human comfort, and aesthetics. In a series of regional analyses based on tree cover, American Forests explored the effect of deforestation on air quality, storm water retention, and carbon sequestration (http://www.americanforests.org/resources/rea/). The broad scale analyses demonstrated the need to not only slow losses but also to increase tree cover to improve benefits.

In analyzing carbon sequestration and air pollution removal, Nowak and Crane (2000) observed wide variation by land use. For example, in Baltimore, Maryland, forest-land use had the highest net rate of carbon sequestration (1,497.8 kg/ha/year) and commercial use had the lowest net rate (305.7 kg/ha/year) (David Nowak, USDA Forest Service, pers. commun.). Like the spatial distribution of birds in different land uses, these findings point to the need for analyses at least to an Anderson Level II to accurately assess the ecological effect of deforestation in an urban landscape. To effectively manage for biodiversity and ecosystem benefits, natural resource managers need to consider not only the recent loss of forest cover but also what the site's future land use. In this paper, fragmentation and deforestation rates in an urban landscape are explored by land use to assess ecological effects and loss of ecosystem services. This assessment identifies how fragmentation and deforestation varies within an urban watershed, affects patch dynamics and connectivity, and reduces the benefits of two ecological services: carbon sequestration and air pollution removal.

Methods

Study area

The study was conducted in the Gwynns Falls watershed, Maryland. The watershed serves as the study area for the Baltimore Ecosystem Study, a National Science Foundation Long-Term Ecological Research Site (Fig. 1). The watershed extends from Baltimore County to the City of Baltimore and covers about 17,150 ha. The watershed is dominated by an urban land use (74.3 % in 1990) and a population that exceeds 356,000. Since the 1950s, the human population has shifted from the urban core to the suburbs. To capture this shift in populations, the watershed is divided into three subsections: lower (urban core), middle (older suburbs), and upper (newer suburbs).

The watershed's vegetation has changed extensively since European settlement. By 1929, Baltimore County, which contains most of the Gwynns Falls watershed, was only 29 % forested. By 1985, forest cover in the county was reduced to 21.3 %. Two community associations dominate upland vegetation: the chestnut oak on coarser soils weathered from schist, and the tulip poplar on saprolitic soils weathered from gneiss and granite (Brush et al. 1980). Riparian vegetation consists of a boxelder-red maple-sycamore association.

Mapping

Tree-covered patches were mapped by combining remote sensing and geographic information system (GIS) technologies, global positioning systems (GPS) and traditional field

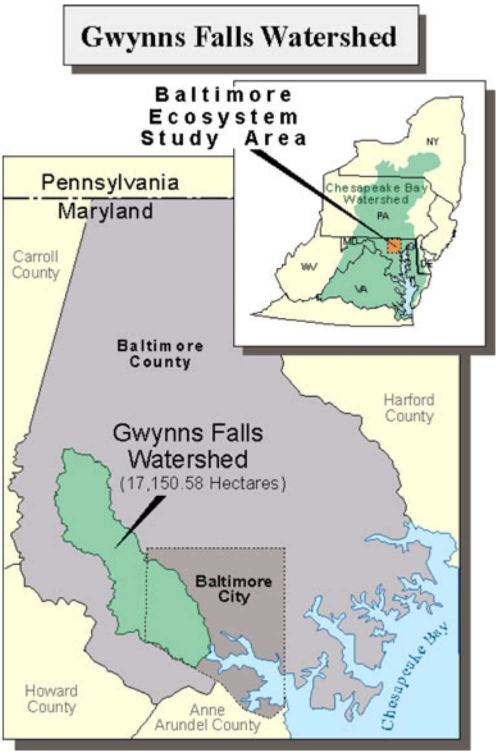

Fig. 1 Location of the Gwynns Falls watershed in Baltimore County, Maryland and the City of Baltimore

mapping techniques. Color infrared digital ortho-quarter quadrangles (DOQQ's), taken in 1994 (leaf-off) by the State of Maryland's Department of Natural Resources (MD DNR), were used to create a base map of tree-covered patches within the Gwynns Falls watershed. The DOQQ's yielded a resolution of 1 m per pixel and were projected in the Maryland State Plain or Lambert Conformal Conic map projection using the 1927 North American Datum (NAD27). Each tree-covered patch (>120 m^2) was digitized on screen by the University of Maryland Baltimore County Spatial Analysis Lab (UMBC-SAL) using ArcView 3.x GIS software, an Environmental Systems Research Institute (ESRI) product. Lab managers conducted quality control procedures regularly to insure data quality by regularly reviewing photo-interpretations and digital images. Mapped patches included street-side, yard, and park trees as well as forests that may or may not contain an understory (Hobbs 1988; Zipperer et al. 1997). Field surveys revealed that patches ≥1 ha were often forests with an understory. Smaller patches included private and public trees with and without an understory.

Once digitized, the tree-covered patches were field checked. Patches were randomly selected, using a stratified random sampling technique, by size class and sub-watershed. In addition, each plot's map coordinates were generated and downloaded into Trimble Pro XR Global Positioning System (GPS) units. The GPS units were used to accurately locate plots (within 1 m) in the field. Eighty-three plots were established to validate mapping accuracy. Accuracy was more than 95 % for patches ≥1 ha and 90 % for patches ≤1 ha.

High-resolution digital ortho-photo aerial photographs (1 m resolution) of the watershed were obtained in 1999. The photos were leaf-on and used a Universal Transverse Mercator (UTM) projection. To overlay the 1994 tree-covered patch map with the photographs, DOQQ maps were projected to UTM coordinates. By overlaying the patch maps onto the photos, fragmentation and deforestation were detected and recorded for individual patches. Primary land uses were urban, agriculture, forest and water (Anderson et al. 1976). Urban was further divided into residential, commercial, and transportation. Land use conversions to residential, commercial, institution, transportation, open, agriculture and other were noted, as was the addition of forest cover due to reforestation.

Habitat characteristics

In addition to measuring fragmentation and deforestation, patch shape and density were evaluated to assess how these attributes changed between 1994 and 1999. Shape was defined by the Patton shape index, $DI = P/2\sqrt{\pi A}$, where P is the perimeter and A is the area of a patch (Wetzel 1983; Forman 1995). Regular shaped objectives (squares, rectangles, and circles) have values at or near 1. As the shape becomes more complex, the index value increases. Although no shape index is perfect, this index was chosen because it is simple to calculate, suitable for the domain of interest and quantitatively differentiates shapes in an understandable manner.

Fragmentation and deforestation increase patch isolation and reduce connectivity (Saunders et al. 1991). In urban landscapes, dispersal can be severely impacted by a high road density, patch isolation, inhospitable habitats and the lack of linear features connecting habitat patches. To examine connectivity, we used the density of patches of different size classes at different dispersal distances from a reference patch. For example, within 50 m of a 10 ha forest patch, the following patch density may be observed: 100–1.0 ha; 10–50 ha; and 1–100 ha. By reporting patch density, availability of "stepping stones" across a landscape for dispersal can be assessed (see Forman and Collinge 1996). Patch density was measured for any patch ≥10 ha at two dispersal distances, 100 and 500 m. Ten hectares was selected as the minimum patch size potentially containing interior forest habitat (Levenson 1981). A general linear model was used to examine differences in mean patch size, shape and density among the watershed subsections within a time period, 1994 or 1999. A simple paired *t*-test was used to identify significant differences of mean patch size, shape and density between time periods, 1994 vs. 1999, within a subsection. Significance was sent at an alpha level of 0.05.

Ecosystem benefits: Carbon sequestration and air pollution removal

To estimate losses in ecosystem benefits from deforestation and fragmentation, we used results from the urban forest effect model (UFORE) (Nowak and Crane 2000, 2002) for the city of Baltimore. Vegetation data was collected by the USDA Forest Service, Syracuse Research Unit (David Nowak, personal communication) in 1998. To inventory the city, 200 vegetation plots were sampled. These plots were stratified land use, and the number of plots per land use was determined by the relative area of the land use in the city. In other words, larger the land-use area, greater portion of plots were placed in that land use. Data collection involved inventorying by species all trees (diameter at breast height, tree height, canopy height and width) and shrubs (shrub height, width and basal diameter). Detailed descriptions of the sampling protocols and model can obtained at http://www.fs.fed.us/ne/syracuse/Tools/tools.htm (Nowak and Crane 2002).

UFORE used the vegetation plot data as well pollution data from local monitoring sites to estimate the amount of carbon sequestered and air pollution removed by trees and shrubs for an entire city or by land use. These estimates were used to determine losses of carbon storage and sequestration, pollution removal, and their monetary value from land-use conversions between 1994 and 1999.

Results

In 1994, the Gwynns Falls watershed had 3,353 tree-covered patches ≥120 m^2 representing 4855.8 ha of canopy cover or 28.3 % of the total watershed area. As expected, the percentage of total number of tree-covered patches (86.2) was greatest for <1 ha (Table 1). Only seven patches were ≥100 ha. Two of these corresponded to a city park (Leakin Park) in the lower subsection of the watershed and a third was a state park (Soldier's Delight) in the upper subsection. Distribution of tree-covered patches in 1994 revealed 1,269 tree-covered patches in the lower, 1,177 in the middle, and 907 in the upper subsections. The lower and middle subsections were characterized by a higher percentage (97.3 and 97.6, respectively) of the total number of tree-covered patches <5 ha than the upper subsection (92.5). The upper subsection had a higher percentage (7.5) of the total number of patches ≥5 ha.

In 1994, the lower and middle subsections had similar total mean patch size (0.9 ha), whereas the upper subsections had a mean patch size of 2.9 ha (Table 2). Although not statistically significant, mean patch sizes by size-class were smaller in the lower subsection than the other subsections. Shape analyses indicated that tree-covered patches <10 ha in the lower subsection were more complex than those in the middle or upper subsections (Table 3). The upper subsection had greater shape complexity for patches ≥50 ha when compared to the lower and middle subsections.

The net number of tree covered patches increased by 78 from 1994 to 1999 (Table 1), but this increase does not reflect the entire landscape dynamics: 125 new tree-covered patches were added through fragmentation, 4 were added through reforestation, 42 were lost through deforestation; and 7 were lost through consolidation (combining with an adjacent patch to

Table 1 Number of tree-covered patches by size class in lower, middle, and upper subsections of Gwynns Falls watershed, Maryland

Patch size (ha)	Lower		Middle		Upper	
	1994	1999	1994	1999	1994	1999
< 1.0	1,107	1,121	1,052	1,070	734	774
1.0–4.9	129	131	91	89	105	121
5.0–9.9	18	15	16	13	31	30
10.0–49.9	12	12	16	16	30	27
50.0–99.9	1	1	1	1	3	3
≥100.0	2	2	1	1	4	4
Total	1,269	1,282	1,177	1,190	907	959

form a larger one). The distribution of patches by size class was similar to that observed in 1994 (Table 1) as 28 new fragments were added in the lower, 24 in the middle, and 73 in the upper subsection of the watershed. The 1994–99 comparison also revealed that the largest patches remained relatively intact. Only one patch (#1531) changed significantly in size and shape. Originally 601 ha with a shape index of 10.6, this patch was fragmented into five patches ranging in size from 0.05 to 501 ha. The largest patch had a shape index of 9.4, indicating simplification. Patch losses were primarily in the middle classes: 5.0 to 9.9 ha and 10 to 49.9 ha (Table 1). For the 5.0–9.9 ha class, three patches were lost in the lower, three from the middle, and one from the upper subsection. The upper subsection lost three patches in the 10 to 49.9 ha class.

Losses were reflected in changes in mean patch size and shape (Tables 2 and 3). Mean patch size decreased in the middle (from 68.5 to 53.5 ha) and upper (from 73.5 to 70.7 ha) subsections for the 50.0–99.9 ha classes and in the lower subsection for the 10.0–49.9 ha class (from 19.1 to 18.0). By comparison, mean patch shape remained comparatively unchanged in each subsection from 1994 to 1999. A comparison among subsections, however, showed that the lower subsection was relatively more complex in the smaller size classes and less complex in largest size class than the middle and upper subsections (Table 3).

Table 2 Mean (S.E.) area (ha) of tree-covered patches by size class in lower, middle and upper subsections of Gwynns Falls watershed, Maryland

Patch size (ha)	Lower		Middle		Upper	
	1994	1999	1994	1999	1994	1999
<1.0	0.2 (0.01)	0.2 (0.01)	0.2 (0.01)	0.2 (0.01)	0.2 (0.01)	0.2 (0.01)
1.0–4.9	2.1 (0.08)	2.1 (0.08)	2.2 (0.11)	2.2 (0.12)	2.2 (0.10)	2.2 (0.10)
5.0–9.9	6.4 (0.34)	6.5 (0.38)	6.7 (0.31)	6.8 (0.24)	7.0 (0.28)	7.2 (0.28)
10.0–49.9	19.1 (3.04)	18.0 (2.40)	20.8 (2.35)	20.3 (2.2)	23.2 (2.19)	23.4 (2.25)
50–99.9	68.3	68.3	68.5	53.5	73.5 (7.10)	70.7 (8.66)
≥100	118.6 (16.32)	118.6 (16.32)	202.4	196.6	266.4 (113.27)	232.0 (90.44)
Overall mean	0.9 (0.16)	0.9 (0.16)	0.9 (0.20)	0.9 (0.20)	2.9 (0.76)	2.9 (0.76)

Table 3 Mean (S.E.) patch shape index by size class for tree-covered patches in lower, middle and upper subsections of Gwynns Falls watershed, Maryland

Patch size (ha)	Lower		Middle		Upper	
	1994	1999	1994	1999	1994	1999
<1.0	2.0 (0.02)[ab]	2.0 (0.02)[ab]	1.8 (0.02)[b]	1.8 (0.02)	1.9 (0.02)	1.9 (0.02)
1.0–4.9	3.3 (0.08)[ab]	3.3 (0.08)	3.0 (0.10)	3.0 (0.10)	2.8 (0.09)	2.8 (0.09)
5.0–9.9	4.1 (0.33)[ab]	4.2 (0.38)	3.0 (0.23)	2.8 (0.23)	3.5 (0.23)	3.4 (0.21)
10.0–49.9	3.9 (0.34)	3.8 (0.35)	4.1 (0.39)	4.1 (0.38)	4.6 (0.29)	4.5 (0.28)
50–99.9	6.9	6.9	3.3	3.8	6.2 (0.50)	6.0 (0.68)
≥100	5.9 (0.19)	5.9 (0.19)	9.21	8.8	8.4 (1.07)	8.0 (0.94)
Total	2.2 (0.03)	2.2 (0.02)	2.0 (0.02)	2.0 (0.02)	2.2 (0.04)	2.2 (0.03)

[a] Significantly different from middle subsection within same year, $P<0.05$

[b] Significantly different from upper subsection within same year, $P<0.05$

From 1994 to 1999, 220 tree-covered patches were reduced in size and 42 patched were deforested by urban land-use conversions in the watershed overall. Even with these losses, 64 tree-covered patches increased in size (Table 4). In all, 264.5 ha of tree cover were lost to urban land-use conversions, but 35.9 ha were gained through canopy expansion and reforestation. The lower subsection lost 6.2 ha of tree cover, the middle subsection lost 42.6 ha, and the upper lost 179.8 ha to urbanization. Losses in the lower subsection were offset by gains elsewhere in tree cover. These were small, incremental additions to existing tree cover.

The type of urban conversion depended on the location within the watershed (Table 4). In the lower subsection, more sites were converted to commercial sites; however, residential use consumed more area of tree cover than commercial use did (13.2 and 11.7 ha, respectively). In both the middle and upper subsections, residential was the dominant land-use conversion and consumed the most land. Because of the need for new roads, transportation conversion also occurred at a higher amount in the upper subsection (8.1 ha) than the middle (0.1 ha) and lower (0.9 ha) subsections. Transportation principally fragmented a patch into smaller ones and accounted for 14 % of the new patches in the upper subsection.

Table 4 Number of tree-covered patches changed or converted to a different land use/cover and resulting change in amount of forest area (lost) in each subsection of Gwynns Falls watershed, Maryland between 1994 and 1999

Land use/cover	Lower		Middle		Upper	
	Patches (N)	Area (ha)	Patches (N)	Area (ha)	Patches (N)	Area (ha)
Forest	41	21.3	6	4.1	17	10.5
Residential	5	(13.2)	28	(37.2)	86	(129.9)
Commercial	29	(11.7)	5	(4.3)	29	(44.9)
Transportation	2	(0.9)	1	(0.1)	15	(8.1)
Open	5	(0.4)	22	(5.1)	20	(2.3)
Agriculture	0	0	0	0	4	(1.4)
Miscellaneous	2	(1.3)	1	(>0.0)	8	(3.7)
Total area lost		(27.5)		(46.7)		(190.3)

Connectivity

Because of fragmented habitats, urban structure, and road density, some species may find an urban landscape rather hostile as they try to maneuver across it. To evaluate connectivity, we assessed the number of tree-covered patches 100 and 500 m from each patch ≥10 ha. Analyses showed that the density of patches surrounding patches ≥10 ha did not change significantly within the 100- and 500-m buffers from 1994 to 1999 by subsection and among subsections (Table 5). The watershed, however, was highly fragmented and disconnected, and patches ≥50 ha were infrequent and clumped (Fig. 2). The analysis also pointed towards the importance of small tree-covered patches (<5 ha) as "stepping-stones" across the urban landscape. In addition, a corridor containing large patches existed only because of the retention of riparian habitat. The lack of large patches in these urban and urbanizing landscapes present a major obstacle for managing or conserving interior species.

Loss of ecosystem benefits

The conversion of forest lands to urban-land uses lower stored carbon and sequestration rates (Table 6). For the entire watershed, fragmentation and deforestation changed total carbon storage from 1994 to 1999 by 14,561,452.0 kg and carbon sequestration of 190,251.7 kg/year, respectively. Losses were partially offset by the addition of forest cover (35.8 ha), which contributed over 2,861,000 kg of carbon stored and over 53,700 kg/year sequestered. Compared to forested land uses, commercial and transportation land uses showed the greatest loss of carbon storage (68,520.6 and 73,068.1 kg/ha, respectively) and sequestration (1,191.9 and 1176.3 kg/ha/year, respectively). In the lower subsection, the conversion to commercial land use had the largest losses for storage (801,691.0 kg) and sequestration (13,945.2 kg/year). Conversion to residential had the largest losses for storage (1,878,715.3

Table 5 Mean patch density (S.E.) by patch size (ha) of all patches within 100 m and 500 m of patches ≥10.0 ha in the Gwynns Falls watershed, Maryland

Patch size (ha)	Lower		Middle		Upper	
	1994 (n=15)	1999 (n=15)	1994 (n=18)	1999 (n=18)	1994 (n=37)	1999 (n=34)
100 m buffers						
<1.0	10.6 (2.4)	12.2 (2.4)	12.1 (1.6)	10.9 (1.3)	8.0 (1.2)	9.7 (1.4)
1.0–4.9	1.8 (0.3)	1.9 (0.3)	2.8 (0.5)	2.9 (0.6)	2.7 (0.4)	3.1 (0.4)
5.0–9.9	0.8 (0.2)	0.7 (0.2)	0.6 (0.2)	0.6 (0.2)	0.8 (0.2)	0.9 (0.2)
10.0–49.9	0.7 (0.2)	0.6 (0.2)	1.6 (0.3)	1.1 (0.2)	1.4 (0.2)	0.8 (0.2)
50.0–99.9	0.2 (0.1)	0.3 (0.1)	0.0 (0.0)	0.1 (0.2)	0.2 (0.1)	0.2 (0.1)
≥100.0	0.3 (0.2)	0.3 (0.2)	0.2 (0.1)	0.2 (0.1)	0.3 (0.1)	0.3 (0.1)
500 m buffers						
<1.0	51.7 (6.9)	50.8 (6.6)	59.7 (5.6)	58.6 (6.0)	33.8 (4.7)	39.3 (6.1)
1.0–4.9	7.4 (0.9)	7.4 (0.9)	7.1 (1.0)	6.8 (1.0)	7.0 (0.6)	8.8 (0.8)
5.0–9.9	1.6 (0.4)	1.3 (0.5)	1.8 (0.2)	1.7 (0.3)	2.2 (0.3)	2.5 (0.3)
10.0–49.9	1.8 (0.4)	1.8 (0.4)	2.6 (0.4)	2.3 (0.3)	3.1 (0.4)	2.0 (0.3)
50.0–99.9	0.4 (0.1)	0.4 (0.1)	0.1 (0.1)	0.2 (0.1)	0.5 (0.1)	0.5 (0.1)
≥100.0	0.6 (0.2)	0.6 (0.2)	0.3 (0.1)	0.4 (0.1)	0.8 (0.1)	0.7 (0.1)

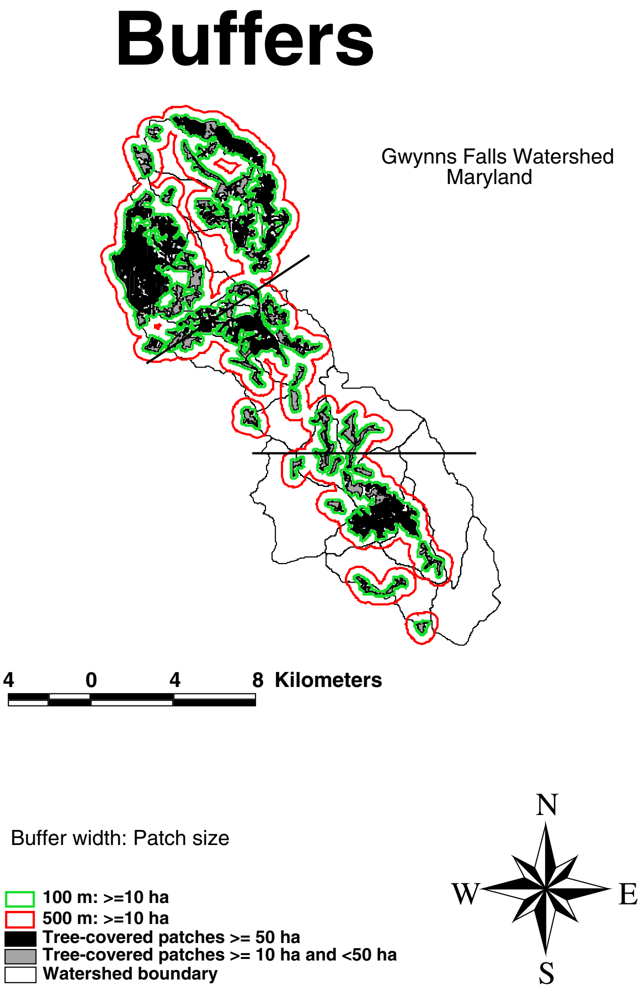

Fig. 2 Observed connectivity in 1999 for two dispersal distances, 100 and 500 m, in Gwynns Falls watershed, Maryland

and 6,560,352.7 kg) and sequestration (20,794.8 and 72,614.1 kg/year) in both the middle and upper sections, respectively.

Deforestation also affected the amount nitrogen dioxide, ozone, particulate matter ≥10 μ (PM10), and sulfur dioxide removed from the atmosphere in this urban/urbanizing landscape. Estimated total pollutant removal declined by 13,266.3 kg. On a per hectare basis, commercial and transportation had the lowest estimated pollution removal rates of urban land uses (Table 7). Vegetation in commercial and transportation removed an estimated 68.0 and 70.4 kg/ha of air pollutants less than forest land use. Like the pattern for estimated carbon storage and sequestration, conversion to commercial land use had the greatest effect on the removal of pollutants in the lower subsection, whereas conversion to residential land use had the greatest effect on the removal of pollutants in the middle and upper subsections.

Table 6 Estimated mean (S.E.) carbon and carbon sequestered per hectare by land use for the City of Baltimore and projected total losses in carbon stored and sequestration by land use from deforestation between 1994 and 1999 in Gwynns Falls watershed, Maryland when forest lands are converted to an urban-land use

Land use/cover	Carbon storage (kg/ha)	Mean gross carbon sequestration (kg/ha/year)	Carbon storage loss (kg)	Sequestration loss (kg/year)
Commercial/industrial	11,180.9 (6379.7)	305.9 (168.2)	4,172,904.6	72,586.7
Forest	79,701.5 (16331.2)	1,497.8 (222.6)		
Urban open	45,886.5 (14789.9)	1,364.9 (513.2)	263,757.0	1,036.6
Medium/low Residential	29,198.4 (5628.1)	938.8 (161.3)	9,105,708.9.1	100,787.7
Transportation	6,632.8 (4682.8)	321.5 (217.4)	664,925.2	10,704.3
Miscellaneous[a]	25,215.9 (3159.3)	707.6 (80.49)	354,156.4	5,136.3
Total			14,561,452.0	190,251.7

Data provided by David Nowak; see Nowak and Crane (2000) for explanation on deriving values

[a] Values for miscellaneous land use category are based on an average for the entire City of Baltimore

Discussion

Urbanization affects landscape structure and ecosystem processes both directly and indirectly. The most obvious direct effect is fragmentation and deforestation of natural cover, which results in smaller and more regularly shaped patches (Godron and Forman 1983). Not surprisingly, we observed a similar effect for tree-covered patches in the Gwynns Falls watershed. Patches increased in number, were more simplistic in shape, and decreased in size. We also identified two subtle patterns not previously reported for urban landscapes. First, tree-covered patches <10 ha in older urban areas increased in shape complexity. This change might reflect patch development, as indicated by numerous forest additions, in established urban areas. As developed areas age, new edges develop from successional processes on abandoned sites, the growth of planted materials, and patch expansion. These changes create a new set of edge/boundary interfaces within an urban landscape that may influence the movement of species, energy, and matter (Cadenasso and Pickett 2000).

The second finding, in-filling through the conversion of small tree-covered patches to residential and commercial land use, further exacerbates the loss of habitat. There are negative ecological and health effects from converting forest use to commercial uses. Blair (1996) reports that the business district (predominately commercial) is the least hospitable

Table 7 Estimated potential reduction of pollutant removal from the conversion of forest to urban land use in the Gwynns Falls watershed, Maryland

Land use/cover	CO (kg/ha)	NO_2 (kg/ha)	O_3 (kg/ha)	SO_2 (kg/ha)	PM10 (kg/ha)
Commercial/industrial	1.9	15.2	23.6	7.8	19.5
Urban open	0.7	5.5	8.6	2.8	7.1
Medium/low Residential	1.2	9.8	15.2	5.1	12.6
Transportation	1.9	15.7	24.4	8.1	20.2
Miscellaneous[a]	1.5	11.7	18.2	6.0	15.0

Data provided by David Nowak; see Nowak and Crane (2000) for explanation on deriving values

[a] Values for miscellaneous land use category are based on an average for the entire City of Baltimore

environment for birds. The conversion of natural habitat to commercial use increases the inhospitable conditions of an urban landscape to avian species and probably other species too. Nowak and Crane (2002) estimated that commercial sites provided the least amount of ecosystem benefits to humans. Even with developed vegetation, commercial sites exhibited the least amount of carbon storage, the lowest carbon sequestration rates, and the lowest pollution removal when compared to other land uses. Consequently, the continual in-filling of tree-covered sites to commercial land use in urban landscapes is especially problematic when considering the health benefits lost to humans and the potential loss of valuable habitat for native species.

Density analyses point out the importance of maintaining existing patches in an urban landscape. Within the Gwynns Falls watershed, connectivity tenuously exists for dispersal distances of >100 m. Connectivity is principally by the retention of the riparian corridors. Although larger patches often are favored over smaller ones with similar habitat value in conservation strategies, both Forman and Collinge (1996) and Hunter (1990) recommend including smaller patches in landscape designs. In agricultural and urban contexts particularly, smaller patches may provide ecological benefits by protecting rare habitats and species outside the large patches; enhancing connectivity between large patches via "stepping stones" for species movement; and enhancing heterogeneous conditions throughout the landscape (Forman and Collinge 1996). In the Gwynns Falls watershed, patches <5 ha may serve as these stepping-stones for species moving across the landscape. The continued in-filling of tree-covered patches increases patch isolation, which may affect species dispersal. Although small tree-covered patches may be beneficial for connectivity, additional research is needed to evaluate their ecological costs as population sinks.

Finally, the ecosystem benefit analyses show direct effects of deforestation on humans and not just wildlife species. Because of deforestation, we estimate that more particulate matter and higher concentrations of SO_2, NO_2 and ozone will occur in the atmosphere; pollutants the otherwise would have possibly been removed by vegetation (Nowak and Crane 2002). Although these values are only estimates, they do provide an insight into how in-filling may affect human at a local or neighborhood level.

Conclusion

Landscapes are dynamic even when dominated by urban land use. Continued deforestation and fragmentation through new conversions to urban land uses create a new landscape mosaic that becomes more inhospitable to species dispersal and reduces ecosystem benefits to humans. Land-use decisions and conservation efforts need to focus on not only maintaining existing forest cover in urban landscapes but also maintaining linkages among patches through a patchwork of habitat stepping-stones. Deforestation also reduces the benefits humans derive from forest ecosystems. To maintain or enhance current tree cover, future development needs to occur on sites already developed or in-filled on vacant sites lacking tree cover. The loss of tree cover and patchwork integrity only makes our species' primary habitat less hospitable.

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