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Measuring and analyzing urban tree cover

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Abstract

Measurement of city tree cover can aid in urban vegetation planning, management, and research by revealing characteristics of vegetation across a city. Urban tree cover in the United States ranges from 0.4% in Lancaster, California, to 55% in Baton Rouge, Louisiana. Two important factors that affect the amount of urban tree cover are the natural environment and land use. Urban tree cover is highest in cities that developed in naturally forested areas (31%), followed by grassland cities (19%) and desert cities (10%), but showed wide variation based on individual city characteristics. Tree cover ranged from 15 to 55% for cities in forested areas, 5 to 39% for those in grassland areas, and 0.4 to 26% for cities developed in desert regions. Park and residential lands along with vacant lands in forested areas generally have the highest tree cover among different land uses. Methods of measuring urban tree cover are presented as are planning and management implications of tree-cover data.

Keywords: Urban tree cover; Photo interpretation; Urban forestry

1. Introduction

Comprehensive information on vegetation in cities is lacking. Although various remote sensing technologies have been used to measure attributes of urban cover (Nowak, 1993a), interpretation of aerial photographs is often the most detailed and cost-effective means of measuring urban tree and other surface cover. Urban tree cover (the proportion of area, when viewed from above, occupied by tree crowns) reveals the extent and variation of the resource across a city. This information provides a more extensive view of urban forests than inventories that focus only on publicly maintained trees.

Measurements of tree cover also provide basic structural data used to model urban forest functions such as air pollution mitigation and carbon dioxide sequestration (Rowntree and Nowak, 1991; Nowak, 1994). Understanding the relationship among urban trees, people, and the environment can facilitate future urban designs that might enhance the environmental and social benefits from trees (e.g. building energy conservation; individual and community well-being; wildlife habitat) (Dwyer et al., 1992).

Tree-cover data in conjunction with ground sampling of vegetation (e.g. tree height, stem diameter,

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species composition, tree health) improve opportunities for comprehensive urban forest planning and management. Comparison of historical and current aerial photos reveals changing land use/land cover patterns, which may also assist in making appropriate urban planning and management decisions (Nowak, 1993b).

This paper reviews several methods for determining urban cover from aerial photographs. Urban tree-cover data are presented from North America and Europe, and relationships among urban tree cover, city, and environmental attributes within US cities are discussed.

2. Methods for determining urban tree cover

2.1. Crown cover scale

Crown cover scale entails placing fixed polygons (e.g. squares) on the photo or dividing the photo into polygons of known size based on ground characteristics or management units (e.g. tree wards). Cover in all polygons can be evaluated, or a sampling of polygons can be conducted. Each polygon that is evaluated is classified discretely by the predominant surface material (Marotz and Coiner, 1973), or percentages of individual cover types within the polygon are estimated using a comparison template as a guide (Moessner, 1947). The template illustrates different percentages of cover, which gives interpreters a means of comparison and standardization when evaluating predefined areas.

If land-use information is not needed, a fixed polygon works best for quick estimates of tree cover. Smaller polygons produce more refined estimates but require more interpreter time. Within each polygon, tree cover can be estimated easily with a template (Moessner, 1947). Estimating predominant surface materials (Marotz and Coiner, 1973) is not recommended because common cover types tend to be overestimated while minor cover types are underestimated.

2.2. Transect method

Randomly located and oriented individual or parallel lines of random or fixed length are made on acetate and overlaid on the photo for sampling. The length of line crossing tree crowns divided by the total length of the line yields percent tree cover (Canfield, 1941; Jim, 1989). Standard errors can be estimated from the variance of the total length of intercept on different lines (Greig-Smith, 1983). Greater accuracy is obtained from more short lines than fewer long lines (Greig-Smith, 1983). Care must be used when using parallel lines in areas with periodic features (e.g. equidistant parallel roads or street trees) because the lines may correspond to the periodic feature and lead to inaccurate estimates of means and underestimates of variance (Scheaffer et al., 1986).

2.3. Dot method

The dot method entails sampling land use and/or cover in the area of interest beneath a series of dots overlaid on a photo. Dots are placed on acetate in a systematic (equal distance between dots) or random fashion. Systematic dots allow for easier data collection, but as with parallel transects, care must be used in cities because of the presence of periodic features. For each dot, the land use and/or cover type under the dot are recorded. The number of the dots falling on tree crowns is divided by the total number of dots recorded to yield percent tree cover. Standard errors for estimates of percent cover can be calculated (Lindgren and McElrath, 1969). The more dots that are analyzed, the lower the standard error and the greater the confidence in the estimate.

2.4. Scanning method

Scanning is the most precise and detailed method of analyzing urban tree cover and integrates well with geographic information systems (e.g. Laverne, 1993). However, it requires special equipment, ortho-rectified photos, and is labor intensive. The boundaries of each cover type are digitized into a data base or shaded in their exact position on individual acetate sheets overlaid on the aerial photograph. Cover area can be measured from the acetate markings with a computer scanner, area meter, or similar equipment.

Cover estimates from digitizers or scanners can be easily incorporated into geographic information systems. These systems aid in vegetation planning and management by revealing spatial relations and interconnections among surface attributes, and referencing vegetation to its exact ground position. Scanning is the most precise method because it measures cover types throughout the entire area without relying on sampling procedures. However, the accuracy of the estimate, as with all methods of cover analysis, relies heavily on the ability of the photo interpreter to correctly classify and input the photo data.

3. US urban tree cover

Data from 58 US cities with a minimum population density of 386 people km^{-2} were analyzed for relationships among cover attributes (percent tree cover, total greenspace, and canopy greenspace), potential natural vegetation type of the city, and population density. These data were compiled from numerous sources (Table 1). Cover estimates did not include city land that was under water (i.e. areas adjacent to lakes, rivers, and bays).

Percent total greenspace is the proportion of photo area filled with vegetation or covered by soil (i.e. not occupied by impervious surfaces or water). Canopy greenspace (percent canopy cover/percent total greenspace) is the proportion of greenspace area filled with tree canopies. It provides an indication of tree dominance within the greenspace area.

The potential natural vegetation of a city is the class of vegetation that, according to Küchler (Küchler, 1967), would exist today if humans were removed and plant succession were allowed to continue to climax condition. For this study, potential natural vegetation types were generalized to forest, grassland, or desert/shrubland (Küchler, 1969).

Estimates of city population (Famighetti, 1994) were based on the date closest to the date of photography used. Population figures were divided by the appropriate city area to determine population density. Land-use proportions were determined from air photo interpretation or by contacting city agencies.

Percent tree cover, total greenspace, and canopy greenspace within potential natural vegetation and land-use types were weighted by the amount of land area analyzed in the corresponding type to derive sample averages and standard errors. Because cities were not selected at random but chosen on the basis of existing data, estimates based on the sample cities may not accurately reflect the characteristics of all cities of a corresponding type or region. Thus, it is possible that statistical comparisons may not meet the stated level of significance. With this warning, simple statistical tests (Mann–Whitney U test, Spearman rank correlation) at the $\alpha = 0.05$ level have been used sparingly to illustrate the strength of differences in the data that might reasonably be expected to reflect corresponding differences in the underlying 'populations'. Differences noted in the following results are based on comparisons at the stated alpha level.

4. Results

Average city tree cover ranges from 55% in Baton Rouge, Louisiana, to 0.4% in Lancaster, California, while percent total greenspace ranges from 93% in Coachella, California, to 38% in Chicago, Illinois (Table 1). Percent canopy greenspace also showed wide variation, ranging from 68% in Atherton, California, to 1% in Lancaster, California (Table 1).

Cities within forested areas have higher percent tree cover and canopy greenspace than those situated in grasslands, which have greater cover and canopy greenspace than cities located in deserts (Table 2). There was no difference among potential natural vegetation types in percent total greenspace in the city. The only difference in city land-use distribution among potential natural vegetation types was that grassland cities had higher 'other land' (agriculture, orchards, transportation and miscellaneous) than forest cities (15.0 vs. 7.2%).

Percent canopy greenspace was negatively correlated with total greenspace in grassland and desert areas (grassland $r = -0.64$; desert $r = -0.83$). Percent total greenspace was negatively correlated with population density ($r = -0.64$) for all cities combined, regardless of potential natural vegetation type.

The largest urban land use is residential and the highest percent total greenspace is on vacant lands (Table 3). Average tree cover and canopy greenspace for residential, institutional, park, and vacant land uses was highest in the forest type (Tables 4 and 5). In forest cities, park and vacant land had the highest

Table 1

Percent tree cover, total greenspace (TGS), and canopy greenspace (CGS) (percent tree cover/percent total greenspace) for 68 cities primarily in North America (only US cities with a population density greater than 386 people km^{-2} (58 cities) were used in land use and potential natural vegetation comparisons)

City	Tree cover	TGS	CGS	Method	Year [a]	Reference
Baton Rouge, LA	55	NA	NA	Planimeter	NA	Blanche et al., 1992
Atherton, CA	47	69	68	Dot grid	1992	USDA FS, 1993 (unpublished)
Waterbury, CT	44	66	67	CCS [b]	1980	USDA FS, 1993 (unpublished)
Portland, OR [c]	42	65	65	Dot grid	1990	McPherson et al. 1993 (unpublished)
Asheville, NC	42	NA	NA	Dot grid	1989	Wooten, 1993 (pers. commun.)
South Lake Tahoe, CA	42	77	54	Dot grid	1992	USDA FS, 1993 (unpublished)
Atlanta, GA [c]	40	63	63	Dot grid	1989	McPherson et al. 1993 (unpublished)
Austin, TX	39	NA	NA	Dot grid	1977	Rodgers and Harris, 1983
Peoria, IL	38	67	57	CCS [b]	1979	USDA FS, 1993 (unpublished)
Birmingham, AL	37	66	56	CCS [b]	1977	Rowntree, 1984
Cincinnati, OH	36	64	56	CCS [b]	1982	Rowntree, 1984
Lawrence, KS	36	63	57	CCS [d]	NA	Marotz and Coiner, 1973
Central, PA [e]	36	69	51	Dot grid	1981	Halverson, 1985
Richmond, TX	34	NA	NA	Dot grid	1977	Rodgers and Harris, 1983
Rock Valley, IA	33	56	58	Dot grid	NA	McPherson et al. 1993 (unpublished)
Dallas, TX [c]	28	56	50	Dot grid	1985	McPherson et al. 1993 (unpublished)
Denver, CO [c]	26	55	48	Dot grid	1988	McPherson et al. 1993 (unpublished)
Salt Lake City, UT	26	59	44	CCS [b]	1977	USDA FS, 1993 (unpublished)
Menlo Park, CA	24	50	48	Dot grid	1992	USDA FS, 1993 (unpublished)
Syracuse, NY	24	55	44	CCS [b]	1978	Rowntree, 1984
Zurich, Switzerland	24	NA	NA	NA	NA	Holscher, 1973
Topeka, KS	23	66	35	CCS [b]	1979	USDA FS, 1993 (unpublished)
Pasadena, CA	22	54	42	Dot grid	1990	USDA FS, 1993 (unpublished)
Dayton, OH	22	58	38	Dot grid	1980	Rowntree, 1984
Eureka, CA	22	61	35	Dot grid	1991	USDA FS, 1993 (unpublished)
New Orleans, LA [f]	21	38	55	CCS [b]	1980	Talarchek and Henderson, 1985
Oakland, CA	21	51	41	Dot grid	1988	Nowak, 1991
Pueblo, CO	21	65	32	CCS [b]	1982	USDA FS, 1993 (unpublished)
Minneapolis, MN [c]	20	45	45	Dot grid	1988	McPherson et al. 1993 (unpublished)
Windsor, Canada	20	NA	NA	NA	NA	Haque, 1987
Sioux Falls, SD	19	68	28	CCS [b]	1976	USDA FS, 1993 (unpublished)
Escondido, CA	18	70	26	Dot grid	1992	USDA FS, 1993 (unpublished)
Kansas City, KS	18	53	34	CCS [d]	NA	Marotz and Coiner, 1973
Yakima, WA	18	58	31	CCS [b]	1982	USDA FS, 1993 (unpublished)
Colima, Mexico [e,aa]	15–20	NA	NA	NA	NA	Haque, 1987
Fresno, CA [c]	17	57	30	Dot grid	1990	McPherson et al. 1993 (unpublished)
Modesto, CA	17	53	32	CCS [b]	1980	USDA FS, 1993 (unpublished)
Ozona, TX [g]	17	NA	NA	Dot grid	1979	Rodgers and Harris, 1983
Baldwin, KS	16	85	19	CCS [d]	NA	Marotz and Coiner, 1973
Eugene, OR	16	68	23	CCS [b]	1982	USDA FS, 1993 (unpublished)
Hong Kong	16	NA	NA	Transect	1986	Jim, 1989
Los Angeles, CA [c]	15	46	33	Dot grid	1984	McPherson et al. 1993 (unpublished)
Redding, CA	15	81	19	Dot grid	1988	USDA FS, 1993 (unpublished)
San Jose, CA	15	58	25	Dot grid	1990	Kerkmann, 1995
Tonganoxie, KS	14	79	18	CCS [d]	NA	Marotz and Coiner, 1973
Sacramento, CA	14	61	23	Dot grid	1992	USDA FS, 1993 (unpublished)
Tucson, AZ [c]	14	57	24	Dot grid	1990	McPherson et al. 1993 (unpublished)
Visalia, CA	12	65	19	Dot grid	1992	USDA FS, 1993 (unpublished)
Yuba City, CA	12	56	21	Dot grid	1992	USDA FS, 1993 (unpublished)
Chico, CA	11	77	15	Dot grid	1990	USDA FS, 1993 (unpublished)

Table 1 (continued)

City	Tree cover	TGS	CGS	Method	Year [a]	Reference
Chicago, IL	11	38	29	Dot grid	1987	McPherson et al., 1993
Eudora, KS	11	72	15	CCS [d]	NA	Marotz and Coiner, 1973
Poway, CA	10	86	12	Dot grid	1992	USDA FS, 1993 (unpublished)
Concord, CA	9	60	15	Dot grid	1992	USDA FS, 1993 (unpublished)
Iraan, TX	9	NA	NA	Dot grid	1979	Rodgers and Harris, 1983
Logan, UT [f]	9	77	12	CCS [b]	1972	USDA FS, 1993 (unpublished)
Coachella, CA [g]	8	93	9	Dot grid	1990	USDA FS, 1993 (unpublished)
El Paso, TX [c]	7	59	12	CCS [b]	1981	Mortimer, 1981
Pecos, TX	7	NA	NA	Dot grid	1979	Rodgers and Harris, 1983
Bakersfield, CA	6	78	7	Dot grid	1990	USDA FS, 1993 (unpublished)
Merced, CA	6	66	9	Dot grid	1990	USDA FS, 1993 (unpublished)
Santa Maria, CA	5	61	9	Dot grid	1992	USDA FS, 1993 (unpublished)
Ciudad Juarez, Mexico [c]	4	57	8	CCS [b]	1981	Mortimer, 1981
Cathedral City, CA	4	82	5	Dot grid	1989	USDA FS, 1993 (unpublished)
Palm Springs, CA [g]	4	88	4	Dot grid	1989	USDA FS, 1993 (unpublished)
Victorville, CA [g]	2	89	2	Dot grid	1992	USDA FS, 1993 (unpublished)
Desert Hot Springs, CA	2	87	2	Dot grid	1989	USDA FS, 1993 (unpublished)
Lancaster, CA	0.4	88	1	Dot grid	1989	USDA FS, 1993 (unpublished)

[a] Year of analysis.
[b] Crown cover scale using tree cover template.
[c] Sample of city census tracts.
[d] Crown cover scale estimating largest cover type in cell.
[e] Average of four cities.
[f] Developed portion of city.
[g] Average population density is less than 386 people km^{-2}.
NA, not analyzed.

Table 2
Mean percent tree cover, total greenspace, canopy greenspace and standard error (SE) for 58 US cities ($n = 53$ for total and canopy greenspace) developed in different potential natural vegetation (PNV) types (Küchler, 1969)

PNV	Tree cover		Total greenspace		Canopy greenspace	
	Mean	SE	Mean	SE	Mean	SE
Forest	31.1	2.6	58.4	2.9	50.9	3.3
Grassland	18.9	1.5	54.8	2.1	32.9	2.3
Desert	9.9	2.4	64.8	4.2	16.9	4.6

Table 3
Mean proportion of city occupied by land use, total greenspace within land use, and standard errors (SE) for US cities ($n = 48$ for proportion of city; $n = 37$ for total greenspace)

Land use	Proportion of city		Total greenspace	
	Mean	SE	Mean	SE
Residential	40.6	2.0	48.8	1.4
Vacant/wildland	23.7	3.0	96.7	0.5
Commercial/industrial	12.7	0.9	26.4	2.0
Other [a]	11.7	1.4	70.1	3.6
Institutional	6.0	0.5	56.0	1.5
Park	5.3	0.6	86.5	1.1

[a] Includes agriculture, orchards, transportation (e.g. freeways, airports, shipyards), and miscellaneous.

Table 4
Mean percent tree cover by land use and standard error (SE) for US cities in different potential natural vegetation (PNV) types (Küchler, 1969) (total $n = 37$ (forest $n = 12$; grassland $n = 18$; desert $n = 7$))

Land use	Forest PNV		Grassland PNV		Desert PNV	
	Mean	SE	Mean	SE	Mean	SE
Park	47.6	5.9	27.4	2.1	11.3	3.5
Vacant/wildland	44.5	7.4	11.0	2.5	0.8	1.9
Residential	31.4	2.4	18.7	1.5	17.2	3.5
Institutional	19.9	1.9	9.1	1.2	6.7	2.0
Other [a]	7.7	1.2	7.1	1.9	3.0	1.3
Commercial/industrial	7.2	1.0	4.8	0.6	7.6	1.8

[a] Includes agriculture, orchards, transportation (e.g. freeways, airports, shipyards), and miscellaneous.

Table 5
Mean canopy greenspace by land use and standard error (SE) for US cities in different potential natural vegetation (PNV) types (Küchler, 1969) (total $n = 37$ (forest $n = 12$; grassland $n = 18$; desert $n = 7$))

Land use	Forest PNV		Grassland PNV		Desert PNV	
	Mean	SE	Mean	SE	Mean	SE
Residential	53.6	3.3	42.6	2.1	33.4	6.1
Park	50.9	6.1	33.7	2.5	12.6	4.0
Vacant/wildland	46.6	7.7	11.4	2.6	0.8	2.0
Institutional	33.5	3.3	16.4	1.9	12.3	3.3
Commercial/industrial	24.8	3.3	25.8	3.7	18.4	2.4
Other [a]	12.9	2.2	9.1	2.1	4.6	1.7

[a] Includes agriculture, orchards, transportation (e.g. freeways, airports, shipyards), and miscellaneous.

percent tree cover; in grassland and desert cities, percent tree cover was highest on park and residential lands (Table 4). Percent canopy greenspace was highest on residential land for all potential natural vegetation types (Table 5).

5. Discussion

Although many factors may influence urban tree cover (Sanders, 1984), two dominant factors affecting the extent and distribution of urban tree cover are the surrounding natural environment and the land use. Surrounding natural environment influences tree cover through the amount of available natural precipitation, as reflected by the potential natural vegetation. Thus, cities developed in areas naturally conducive to tree growth (average annual precipitation exceeds evapotranspiration) generally have the highest tree cover, while cities developed in desert regions generally have the lowest tree cover. Because differences in city land-use proportions among potential natural vegetation types were minimal, differences in overall city tree cover among potential natural vegetation types result primarily from the natural environment and associated management practices (e.g. watering), which are related to the surrounding natural environment.

Although there are broad differences in tree cover among cities based on the surrounding natural environment, tree cover of individual cities depends on land-use distribution in conjunction with the local environment. Waterbury, Connecticut, a city with relatively high tree cover, was developed in a forested area but also has a relatively large amount of vacant land (one third of the city) with 74% tree cover. The two cities with the lowest tree cover are in desert regions and contain large amounts of vacant land (63–76%) with little tree cover (less than 1%).

Within a city, land use is a dominant factor affecting tree cover on a local scale. Each land use has a characteristic structure that creates a certain amount of space available for vegetation, and a characteristic function that helps determine the amount of the potential space that is filled with trees. Vacant land in the forest type and park and residential lands in all areas typically have the highest percent tree cover among land uses. Thus, local benefits from trees are greatest for these land uses. Planners and managers might choose to focus on sustaining tree cover and its associated benefits in these areas and increasing tree cover on less forested land. However, sustained or increased tree cover is not appropriate in all areas (e.g. prairie restoration, desert preservation, active recreational fields). Optimum stocking levels vary depending on the costs of trees and desired site-specific benefits (Richards, 1992).

Humans interact with the natural environment to create differences in tree cover. Costs of maintaining vegetation and attitudes toward trees in the urban landscape, both related to surrounding environmental factors, alter the desire and ability of people to incorporate trees in the urban landscape. Tree cover can be increased by allowing space for vegetation, planting, and/or encouraging natural regeneration. Conversely, tree cover can be reduced through removals, mowing, herbicide applications, or other actions that inhibit tree growth. As the environment becomes more conducive to tree growth, percent tree cover generally increases (Tables 4 and 5). In residential, park, institutional, and vacant lands in forested areas, canopy greenspace is 10–45% higher than for the same land use in grassland and desert regions. On commercial/industrial and 'other' land uses, tree cover and percent canopy greenspace vary little among potential natural vegetation types because land-use function dictates local morphology and often limits the space available for trees, regardless of the natural environment. Development plans can be designed to actively facilitate or eliminate vegetative growth.

Besides providing a basis to assess variations in tree cover across a city's landscape, cover data can be used to determine the benefits provided by city trees. Research has shown a correlation between building energy use and tree canopy cover in several US cities (Huang et al., 1990). For all cities analyzed, annual home energy costs decreased as tree canopy cover increased from 0 to 30%. Total carbon storage and annual carbon sequestration by trees can also be estimated using cover and tree diameter distribution data (Rowntree and Nowak, 1991). Estimates of the effects of trees on atmospheric carbon and building energy use can be used to assess the effects of urban trees on greenhouse gases, and can provide useful information for the Voluntary Reporting of Greenhouse Gases, a program that encourages the reporting of achievements in reducing greenhouse gases (U.S. Department of Energy, 1994).

Cover data can also be useful in quantifying air pollution removal by city trees. In the Chicago area (19% tree cover), estimated average hourly improvement (in-leaf season) in air quality owing to trees ranged from 0.002% for carbon monoxide to 0.4% for particulate matter. Maximum hourly improvement for the area was estimated at 1.3% for sulfur dioxide, though localized improvements in air quality can reach 5–10% in areas with relatively high tree cover (Nowak, 1994). By understanding variations in cover and associated costs and benefits, city planners and managers can develop strategies, such as increasing tree cover in heavily polluted areas, that will improve the urban environment.

Incorporating cover attributes in a geographic information system facilitates vegetation management through spatial analyses that can identify landscape features such as the extent of forest fragmentation, forest patch size and shape, and corridor locations and connectivity. By understanding these features, planners can optimize landscape structure to maintain or enhance such attributes as biodiversity, species movements, and the flows of energy and materials (e.g. Forman and Godron, 1986; Turner and Gardner, 1991; Hansen and di Castri, 1992).

6. Conclusion

The natural environment and humans (via land-use development and management practices) interact in cities to form vegetation patterns. Planners and managers can alter current patterns by changing human tendencies (e.g. by education, ordinances, and tax incentives) and/or changing the vegetative environment (e.g. altering planting, watering, and mowing). Typically, tree cover is sustained most easily in forested regions with efforts to increase or maintain tree cover focused on residential and park land uses. Across the city landscape, the geography of land-use patterns largely governs the amount and spatial arrangement of tree cover.

Data on urban tree cover aids urban planners and managers in determining the extent and distribution of the city's vegetation resource and its associated costs and benefits. It also can reveal patterns and interconnections across the landscape and provide a baseline for quantifying urban forest change. Additional ground data on characteristics such as species composition, tree diameter and height, and tree health can be used to significantly improve the overall urban vegetation data base.

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