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Geospatial methods provide timely and comprehensive urban forest information

Kathleen T. Ward[a,*], Gary R. Johnson[b]

[a]USDA Forest Service, North Central Research Station, 1561 Lindig Street, St. Paul, MN 55108, USA
[b]University of Minnesota, College of Natural Resources, Department of Forest Resources, 1530 Cleveland Avenue North, St. Paul, MN 55108, USA

Abstract

Urban forests are unique and highly valued resources. However, trees in urban forests are often under greater stress than those in rural or undeveloped areas due to soil compaction, restricted growing spaces, high temperatures, and exposure to air and water pollution. In addition, conditions change more quickly in urban as opposed to rural and undeveloped settings. Subsequently, proactive management of urban forests can be challenging and requires the availability of current and comprehensive information. Geospatial tools, such as, geographic information systems (GIS), global positioning systems (GPS) and remote sensing, work extremely well together for gathering, analyzing, and reporting information. Many urban forest management questions could be quickly and effectively addressed using geospatial methods and tools. The geospatial tools can provide timely and extensive spatial data from which urban forest attributes can be derived, such as land cover, forest structure, species composition and condition, heat island effects, and carbon storage. Emerging geospatial tools that could be adapted for urban forest applications include data fusion, virtual reality, three-dimensional visualization, Internet delivery, modeling, and emergency response.

Keywords: GIS, remote sensing, forest management

Introduction

The urban forest may be defined as the assemblage of woody and other vegetation that lies within an urban area, or that forest structure which is regularly subjected to influences of an urban nature (Sanders, 1984). Definitions of urban areas differ, but typically they consist of densely settled territories with population densities of at least 1000 people per square mile (US Census Bureau, 2006). The urban forest includes trees along streets and other rights-of-way, trees in parks and residential yards, and in forested recreational areas near population centers (Rowntree, 1984). Other than trees, components of the urban forest include other plants, animals, people and infrastructure (Dwyer and Nowak, 2000).

Natural processes within urban forests operate under an unusual suite of constraints because the areas are relatively small and isolated, are subject to frequent disturbance, and are impacted by polluted air and waste (Rogers and Rowntree, 1988). Trees are typically under greater stress in urban than in rural or undeveloped areas because of greater urban temperatures, soil compaction, restricted root zones, and variation in the intensity of light and wind caused by buildings and pavement (Flint, 1985). The rigorous conditions render urban forest ecosystems particularly susceptible to pests and diseases, climate change and extremes, acid rain, and air pollution (Metzger and Oren, 2001).

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*Corresponding author.
E-mail address: kward01@fs.fed.us (K.T. Ward).

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Design of a tree maintenance and management strategy not only depends upon an understanding of the environments of urban trees and the stresses on tree health and condition (Talarchek, 1987), but also upon an allowance for the role that politics plays in managing urban forests. For example, more than half of the urban forests in the United States typically occur on residential lands (McPherson, 1993) and access to private property is a unique constraint to monitoring and management of urban forests. Additionally, management issues such as those related to acceptable levels of pests, nonnative invasive species, landowner values, aesthetics, watershed quality, and best management practices must be considered in an ever-changing landscape (Anderson, 2003). Because urban land-use patterns change rapidly in response to economic, social and environmental forces, urban forest planning and management require rapid, accurate, and systematic methods for acquiring information (Sanders, 1984; Bergen et al., 2000; Dwyer and Nowak 2000).

Background

Structure, function and value of the urban forest

Sanders (1984) described urban forest structure as the collection of vegetation above and below the ground within an urban area. McPherson et al. (1997) further described it as the way vegetation is arrayed in relation to other objects, such as buildings. Urban forest structure can be determined by urban morphology, natural factors, and human management systems, and differs according to vegetation characteristics, such as species, age, size, condition, density and distribution (Sanders, 1984). Site factors, such as climate, soils, storm patterns, and the composition of presettlement vegetation, both influence current forest structure and shape perceptions of desired structure (McPherson et al., 1997). Changes in forest structure can influence ecological processes, which in turn can affect environmental quality (McPherson et al., 1997).

Urban forest function pertains to the dynamic operation of the forest through an array of biogeochemical processes acting among individual members of the forest flora and fauna and between the forest and its environment (e.g., nutrient cycling, gas and energy exchange, succession) (Rowntree, 1986). The benefits of specific urban forest functions can be maximized by configuring vegetation in patterns that are unique to the purpose of each landscape (e.g., greenbelt preservation, fire-hazard reduction, water conservation) (McPherson et al., 1997).

The relatively small size of urban forests belies their value unless one considers that large sums of money are dedicated to their management and that the environmental, social, and economic benefits they provide are substantial (McPherson, 1993). McPherson et al. (1997) calculated that the economic benefit of street trees in Chicago, Illinois, USA is potentially three times that of their projected costs. In Modesto, California, USA the average benefit in energy savings, air quality improvements, aesthetic values, and atmospheric carbon dioxide and stormwater runoff reductions for 10 street tree species ranged from 55 to 186 USD per tree per year (McPherson, 2003). The urban forest in the continental United States is estimated to total 3.8 billion trees at a compensatory value of 2.4 trillion USD (Nowak et al., 2002).

Urban forest health

Definitions of forest health abound, but it is most commonly described as a measure or a condition. As a measure of forest ecosystem robustness, dimensions of interest may include rates of growth and mortality, crown condition, and incidence of damage (Steinman, 2004). Forest health can be defined as a condition that is resistant to or tolerant of damage or a condition where damage may have positive attributes, such as dead trees that are perfectly suited for nesting birds. Forest health may be defined in anthropocentric terms such as "…a condition of forest ecosystems that sustains their complexity while providing for human needs" (O'Laughlin et al., 1994, p. 65). However, forest health is often defined more generally as, "a capacity to supply and allocate water, nutrients, and energy in ways that increase or maintain productivity while maintaining resistance to biotic and abiotic stresses" (McLaughlin and Percy, 1999, p. 152).

Sustainability is related to forest health and has become a primary objective in present-day ecosystem management (Coppin et al., 2004). A sustainable urban forest is one that maintains biodiversity, productivity, regenerative capacity, vitality, and the potential to fulfill relevant ecological, economic, and social functions (Wiersum, 1995). The key attributes that have significant implications for sustainability include its diversity, connectedness and dynamics (Dwyer and Nowak, 2000). Diversity of the urban forest is a function of variations in land uses, land ownerships, and management objectives, as well as variable tree species and sizes, ground covers, soil types, microclimates, wildlife, people, buildings, and infrastructure (Dwyer and Nowak, 2000). Connectedness among urban forest patches and other urban environments can occur through plantings (either preserved or introduced) associated with roads, homes, people, industrial parks, and downtown centers (Dwyer and Nowak, 2000).

Urban forest dynamics may be affected by many events, including introductions of exotic plants and animals, and expansion of urban areas and transportation systems over time (Dwyer et al., 2003). Dynamics of the urban forest change continually over time with the introduction, growth, development, and succession of its biological components (Dwyer and Nowak, 2000). The framework for planning and management of a sustainable urban forest is formed by management program goals, means and outcomes; social context; existing and planned vegetation; and available information (Dwyer and Nowak, 2000).

GIS and GPS

There are several available sources of timely and accurate information and methods that can be used in urban forest management in light of rapidly changing influential forces: inventory data, statistics, survey results, resource research, management techniques, and tree health assessment and monitoring techniques. In addition to those, current information on land-use change is the basis for the development of land-use policy to address problems that accompany growth (Ridd and Liu, 1998). In lieu of rapid, accurate and systematic urban forest inventory technology, traditional methods like ground surveys and aerial photography typically have provided much of the necessary information (Kontoes et al., 2000). However, as the notion of urban forestry has broadened over time from traditional street tree management to urban ecosystem management, there are increasing needs for more current and extensive information about urban natural resources (McPherson et al., 1997). Geographic information systems (GIS) and global positioning systems (GPS) are geospatial tools that can provide timely and effective information for urban forest management.

GIS and GPS have been successfully used to map and record detailed characteristics of individual trees. GIS is a computer system that allows users to collect, manage, and analyze large amounts of data that can be linked to geographic locations. GPS is a satellite-based navigation system used to compute and track geographic positions.

GIS has been useful for assessing the spatial pattern and distribution (e.g., age classes, species composition, health status), and environmental functions (e.g., recreation, aesthetics, environmental protection) of the urban forest (Pauleit and Duhme, 2000). In addition, GIS allows for a graphical depiction of the spatial and temporal dimensions of the biological, physical, and demographic attributes related to urbanization and forest resources (Gunter et al., 2000). With the addition of a statistical model to the GIS, predicted changes in urban forest resources could be illustrated as the biological, demographic, and transportation network attributes of the area change (Gunter et al., 2000).

Satellite-borne sensors

Remote sensing is another geospatial tool that refers to methods of gathering information about features without having sensors in direct contact with them. The sensors are typically mounted on satellites or airplanes and are used to identify features by the electromagnetic energy that is reflected or emitted from them. Remotely sensed images differ in spatial, temporal, and spectral resolutions. For example, Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument aboard the Terra and Aqua satellites. Terra and Aqua MODIS view the Earth's surface every 1–2 days; and acquire data in the visible, near, mid and thermal infrared regions in 36 spectral bands. The spatial resolution of MODIS ranges from 250 to 1000 m. The advanced spaceborne thermal emission and reflection radiometer (ASTER) sensor is also mounted on the Terra satellite and is used to obtain detailed maps of land surface temperature, reflectance and elevation. ASTER has a spatial resolution that ranges from 15 to 90 m and captures data in 14 bands, from the visible to the thermal infrared wavelengths. Four sensors with spatial resolutions that range from 15 to 90 m are mounted on the Landsat series of satellites—multispectral scanner (MSS), thematic mapper (TM), enhanced thematic mapper (ETM) and enhanced thematic mapper-plus (ETM+). Data collected by Landsat instruments have been extensively utilized for forestry and other purposes because of the large geographic areas they image and because of the long historical range of data that have been acquired (from 1972 to present). The Satellites Pour l'Observation de la Terre (SPOT) 5 satellite carries sensors with spatial resolutions between 2.5 and 20 m and spectral resolutions in the visible, and near and mid-infrared regions. Data acquired from SPOT 5 sensors have a wide range of applications due to the balance between high spatial resolution and wide-area coverage.

There are several satellite-borne sensors that collect high spatial resolution imagery, such as Quickbird (from 60 to 2.4 m), IKONOS (from 1 to 2 m), and OrbView (from 1 to 4 m). The disadvantages of high-resolution imagery are the relatively low geographic coverage, high cost per image scene, large file sizes, and problems with automated classifications (e.g., mixed pixels, shadow effects). Mixed pixels are those that belong to more than one land cover class. Automated analysis of high-resolution imagery is complicated by the effects of mixed pixels because as spatial resolution increases, spectral within-field variability increases (Ouma et al., 2006). Mixed pixel effects can be addressed with spectral mixture analysis (Small, 2003) and shape- (Segl et al.,

2003) or texture-based (Zhang 2001; Ouma et al., 2006) classification techniques. Shadow effects result when the sunlit and shady sides of features have vastly different spectral responses, even though they belong to the same class (Thomas et al., 2003). However, shadow effects can be minimized by acquiring data at certain times during the day (Dare, 2005).

Airborne sensors

An advantage of airborne sensors as compared to satellite systems is that data acquisition is more flexible in timing and mode. In addition, the spatial resolution of the data can be higher (20 cm or less) as compared to those borne on most satellites. The spatial resolution of data collected by airborne sensors is primarily determined by the altitude of the flight. Some disadvantages of airborne high-resolution imagery are similar to those of high-resolution satellite data as described above.

Airborne data acquisition and registration (ADAR) is an airborne sensor that collects high spatial resolution data (1 m). Thermal airborne broadband imager (TABI) is a relatively new airborne sensor with high spatial (25–1.5 m), spectral (288 bands), and thermal resolution (0.1°). TABI has proved useful in urban areas for the mapping of heat island effects (Pu et al., 2006). Airborne instruments with hyperspectral characteristics, such as compact airborne spectrographic imager (CASI) and airborne visible infrared imaging spectrometer (AVIRIS), can collect information in numerous, narrow spectral bands (288 and 224 bands, respectively). The advantage of a hyperspectral sensor is that it can discriminate much finer differences among features than can a broader band sensor, such as TM.

Light Detection and Ranging (LIDAR) is an airborne system that transmits pulses of laser light to the surfaces of the Earth and measures the time it takes for the light to be reflected or scattered back to the instrument. LIDAR remote sensing is a breakthrough technology for forestry applications because the instrument has demonstrated the capability to accurately estimate several forest attributes, such as canopy heights, stand volume, basal area, and above-ground biomass (Dubayah and Drake, 2000). Synthetic aperture radar (SAR) is another airborne system deployed aboard aircraft or satellites that can be used to detect and locate features by sending out pulses of electromagnetic waves and measuring the return times and directions of the waves. The spatial resolution of SAR data is limited by the width of the pulse, i.e., narrower pulses produce finer data. The advantages of SAR are that images can be acquired day and night independent of solar illumination, and the long wavelengths of SAR can penetrate clouds, tree canopies, and soil. A disadvantage of SAR data is that each pixel has to be analyzed within its environment by a statistical or textural approach instead of at the pixel level as in optical imagery (Basly et al., 2000).

Applications

The electronic format of satellite and digital aerial imagery allows it to be readily integrated into a GIS. Employment of a combination of GIS, remote sensing technology, and ground sampling of vegetation characteristics is an ideal strategy for collecting timely urban forest information (Kontoes et al., 2000). The wide field of view of urban land cover provided by satellite and airborne sensors is an important complement to in situ measurements of the physical, environmental and socioeconomic variables in urban settings (Small, 2001). The temporal, spatial, and spectral resolution of the data, the complexity of the urban setting, and the cost and timing of data acquisition can affect the choice of remotely sensed imagery (Kontoes et al., 2000).

High spatial resolution imagery is particularly well suited for urban applications because the spatial scale allows for more detailed mapping of individual features as compared to moderate spatial resolution imagery (Thomas et al., 2003). Digital, high spatial resolution aerial imagery was used successfully to delineate urban cover classes in Syracuse, New York, USA (Myeong et al., 2001), to map pervious and impervious surfaces to aid in storm-water run-off control in Scottsdale, Arizona, USA (Thomas et al., 2003), and to assess the urban heat island effect in Huntsville, Alabama, USA (Lo et al., 1997). Digital aerial photography was also utilized for the detection of stress of bur oak trees (*Quercus macrocarpa* Michx.) associated with soil compaction in a Minnesota park (Hargrave, 2001), and damage from Sudden Oak Death in oak (*Quercus* spp.) and tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rheder) in California (Kelly et al., 2004). Urban environments were mapped successfully using data collected by the hyperspectral sensors AVIRIS in Modesto, California, USA (Xiao et al., 2004) and CASI in Tel-Aviv, Israel (Ben-Dor et al., 2001).

Alternatively, researchers have suggested the use of satellite imagery for urban forest management because it provides regular and up-to-date information in a variety of spectral, spatial and temporal resolutions (Kontoes et al., 2000). Landsat imagery was used to map land cover in metropolitan areas in the American cities of Minneapolis/St. Paul, Minnesota (Yuan et al., 2005); Atlanta, Georgia (Yang and Lo, 2002); Chicago, Illinois (Iverson and Cook, 2000); and Ottawa, Calgary, and Ontario, Canada (Guindon et al., 2004). Landsat data has also been used to map urban thermal characteristics in Tampa Bay, Florida and Las Vegas, Nevada (Xian and Crane, 2006), and to estimate urban forest carbon storage in Syracuse, New York (Myeong et al., 2006). Data from the TABI, ASTER, and MODIS sensors were used to map urban surface temperatures in Yokohama City, Japan (Pu et al., 2006). Imagery acquired from satellite-mounted SAR sensors was used effectively to map urban change within South Wales (Grey et al., 2003), and to analyze urban land use patterns in Nantes, France (Basly et al., 2000).

Many issues associated with landscape change over time are currently of major importance to land managers and planners. In the continental US, 21.7 million acres of currently rural or exurban land are projected to be converted to urban land by 2030 (Stein et al., 2005). In the seven-state Midwest Region of the US, urban land cover increased by 24% and population density increased by 10% between 1980 and 2000 (Potts et al., 2004). A decrease of 8% in forest area and an increase of 38% in urban land area between 1986 and 2002 in a seven-county metropolitan area in Minnesota was determined using TM satellite imagery (Yuan et al., 2005). MSS and TM data were used to detect land use and land cover changes over a 25-year period in Atlanta, Georgia, where urban sprawl contributed to decreases of 21% of forest area and 33% of crop/grassland area (Yang and Lo, 2002).

Monitoring urban forests also helps managers to better define, detect, and predict urban forest condition (McPherson, 1993). Remotely sensed images are readily applicable to operational assessment of forest physiological stress, and classification and change detection of forest condition. Forest condition indicators may include stand growth, foliar symptoms, and landscape patterns (Riitters et al., 1992). Stand growth can be estimated from remotely sensed imagery through use of a leaf area index (LAI), which is the ratio between the total leaf surface area of a tree and the surface area of ground that is covered by a tree. LAI is directly proportional to important processes such as canopy interception, transpiration, and net photosynthesis because leaf surfaces are the primary sites of energy and mass exchange (Pierce and Running, 1988). ASTER data were used efficiently to determine LAI at 143 urban sites in Terre Haute, Indiana (Jensen and Hardin, 2005).

Stress and reduced vitality can affect the spectral signatures of green plants through decreases in near infrared wavelengths and increases in visible wavelengths, and these changes can be detected by remote sensors (Hagner and Rigina, 1998). Bark beetle damage on Jeffrey pine (*Pinus jeffreyi*, Grev. & Balf.) was effectively detected using ADAR imagery in a state park near San Diego, California (Hope and Stow, 1993). Hargrave (2001) derived a greenness scale from imagery acquired by a helicopter-mounted digital camera to determine the condition of bur oak trees in a Minneapolis, Minnesota Park. In addition, changes in urban landscape structure can be assessed from remotely sensed imagery through use of fragmentation indices (Riitters et al., 1992). Forest types classified from TM and MSS data were utilized to map forest stands and to determine forest fragmentation statistics in the Regional Municipality of York, Canada (Puric-Mladenovic et al., 2000). The authors found that forest cover decreased by 7% in a 13-year period and that the forest ecosystem had been broken up into smaller parcels that changed in both their structure and function (Puric-Mladenovic et al., 2000). Forest cover types classified from Landsat MSS imagery and fragmentation statistics were utilized to examine rates and patterns of coniferous forest landscape change in the Klamath-Siskiyou ecoregion, OR and CA (Staus et al., 2002). The authors found that forest cover in the ecoregion decreased by 5% and forest patches decreased in size and connectivity during a 20-year period.

Emerging technologies

Several emerging geospatial technologies already in use in urban forest applications and some that could be readily adapted include three-dimensional (3D) visualization, virtual reality, Internet product delivery, and integrated disaster response. In 3D visualization, points are measured in 3D by airborne scanners and are then displayed on a digital terrain surface (Haala and Brenner, 1999). Topographic features are extracted automatically and urban vegetation like trees and shrubs can be depicted through a combination of 3D points and color imagery (Haala and Brenner, 1999; Toutin, 2004). The 3D visualizations can assist in urban planning and management and can be used to investigate and model air pollution and air flow (Maktav et al., 2005). Virtual reality 3D systems have also been developed that are capable of realistic walk-through simulations of forest landscapes (Lim and Honjo, 2003). Data visualization and virtual reality systems enable forest managers to consider alternative plans realistically so that landscapes may be more efficiently managed (Lim and Honjo, 2003). Visualization techniques, along with GIS and Internet technology can bring greater and faster public access to information. For example, OakMapper is an Internet-based application that facilitates the collection of data from a wide community of users concerning trees suspected of being infected with Sudden Oak Death in California (Kelly and Tuxen, 2003). The application combines data input, map presentation, and database queries, and facilitates community involvement in environmental monitoring (Kelly and Tuxen, 2003). There are many other websites that offer visualization and animation of urban environments. The National Aeronautics and Space Administration (2006) offers urban land signatures (e.g., heat flux, evaporation, temperature) and urban growth visualizations. In addition, several interactive geospatial urban maps and downloadable datasets are available through the US Geological Survey (2006). Another instance of recent technology that could be ideal for urban forest use is near real-time fire monitoring and forecast using an integrated framework of satellite remote sensing, GIS, and interactive communication capabilities (Keramitsoglou et al., 2004).

Discussion

The utility of geospatial tools has been proven; however, they could be more widely adopted by urban forest managers if some of the common barriers to their use were overcome. Tools and software need to function almost intuitively for wide acceptance by urban forest managers who may primarily be experts in forest health, care or planning, but not the latest electronic technology. Currently, many tools or programs require a high level of technical sophistication that few practicing foresters possess. To further complicate the issue, many communities contract with specialists to use the evaluative tools and software to develop baseline information and foundations for management plans. However, once the expertize of the contracted specialists is no longer available, quite often the tools are put aside and eventually become outdated and useless to the community and the urban forest manager.

Another barrier to widespread use of geospatial tools is the lack of specific knowledge of baseline vigor levels of the tree species and environs of interest. For instance, high spatial resolution digital aerial photographs have been successfully used to detect the presence of tree stress. However, stress is a measurement relative to an implied baseline condition or vigor level. Vigor of young trees almost always differs from that of mature trees. Trees growing in native soil with little amorphic materials covering the surface will have different vigor levels than trees of the same species growing in highly altered soils and/or in situations where the soil surface is primarily impervious. And yet, all of these trees could be considered relatively healthy. Therefore, much research remains to be conducted to establish baseline vigor levels of different tree species at varying ages under many site conditions if notable alterations from the norm are to be detected using imagery with high spatial resolution.

Detection limitations of geospatial tools may also present challenges to the urban forest manager. The spatial resolution of the chosen imagery should allow detail that is fine enough for detection of the desired forest features. A manager of a relatively small urban forest or community may need to focus on health issues of individual trees or neighborhoods. Management of larger communities or urban forests may concentrate on a single species, such as ash (*Fraxinus* spp.) in areas vulnerable to the emerald ash borer (*Agrilus planipennis* Fairmaire) insect pest, or maple (*Acer* spp.) in areas undergoing gypsy moth (*Lymantria dispar* L.) infestation. Digital imagery with high spatial resolution such as from digital aerial photography or from sensors mounted on the IKONOS or Quickbird satellites would be critical for use as a management tool in those situations. In situations where less detail and larger geographic coverage may be necessary, the moderate spatial resolution of TM or ASTER satellite imagery may suffice. Other considerations for choice of imagery may include the desire for repeated measurements of the same area over time, and of the costs for acquisition and interpretation.

Urban forests can provide significant management challenges not often found in rural or undeveloped forests because they are populated by both native and introduced species, share growing spaces with buried and surrounding urban infrastructure, commonly grow in highly altered soils, and are often subjected to vandalism and pollution. Fortunately, many urban forest management issues can be quickly and effectively addressed using geospatial tools and methods. For example, sustainable forest management requires information about the health status and growth rates of urban trees. The condition of urban tree foliage could be determined quickly and reliably from satellite or digital aerial imagery through the use of vegetation indices that are formed by using ratios of the appropriate wavelengths (Riitters et al., 1992). In addition, GIS is an ideal tool for spatially depicting and tracking tree information over time.

Another issue is the increasing fragmentation of unmanaged forests near expanding major cities or suburban areas. As a result of fragmentation, forest connectedness among habitat areas required for wildlife movement and survival may be affected. Through use of a GIS, the spatial patterns of the forest can be mapped so that managers can effectively direct efforts to selected habitat areas. Fragmentation is also a predisposing agent that directly and indirectly affects the health of remnant trees and wooded areas. Outbreaks of forest insect pests and diseases, and the spread of invasive plants and animals are of increasing concern in areas where overall forest vigor has been compromised by fragmentation. The presence of some insects and diseases and invasive pests can be detected using remote sensing, and can be monitored over time and analyzed using a GIS. Control tactics and treatments can be more effectively timed in terms of season or tree phenology as well as before damage thresholds are exceeded. Additionally, GIS and statistical software can be used to develop predictive models to delineate and monitor forest areas that are more likely to be affected in the future. Predictive models can allow managers to take preemptive measures that lessen the effects of diseases, insect pests or invasive plants.

Conclusions

Geospatial tools have a wide variety of applications from the creation of basic maps of structure, composition and extent of the forest to complex forest disturbance models. A major advantage of the use of geospatial tools as compared to traditional ones is that they provide information on the forest resource that is both current and comprehensive. In an urban forest setting where conditions change rapidly there may be no greater benefit to forest managers than timely and extensive forest resource information.

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