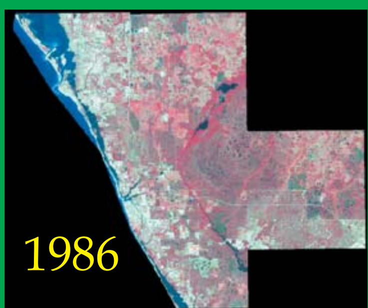


Urban Ecosystem Analysis for Sarasota County

March 2004

Sarasota County
PBS&J
USF University of South Florida
Florida Center CD+R

Urban Ecosystem Analysis for Sarasota County

Prepared for:

Sarasota County

Public Works
Forestry Division
1001 Sarasota Center Boulevard
Sarasota, Florida 34240

Prepared by:

PBS&J
2803 Fruitville Road
Suite 130
Sarasota, Florida 34237

Final Report

March 2004

Executive Summary

Sarasota County covers a land area of approximately 370,000 acres or 580 square miles. Before widespread colonization by European settlers, the County was characterized by a variety of natural vegetation communities including pine flatwoods, hardwood hammocks, scrub, prairies, fresh and saltwater marshes, mangrove forests, and seagrass beds. Although large portions of the County are still comprised of native vegetation cover, urban and agricultural development has had a significant impact on these natural systems. This has resulted in changes of both wetland and upland vegetation during the past century.

As urban areas in the County continue to expand, evaluating and managing the remaining urban forests has become increasingly important. Urban forests are now being recognized as a form of infrastructure that can provide many ecosystem services to local communities. Previous studies have shown that urban forests reduce stormwater runoff, reduce certain air pollutants, sequester carbon, reduce residential and commercial energy use, and improve property values.

This study was performed for the Sarasota County Forestry Division to evaluate large scale (County-wide) changes in vegetation coverage over the past 30 years and also to evaluate the functions and values of the urban forest with respect to stormwater runoff, energy savings, and air quality. The results of this study were also compared to other similar studies which have been performed throughout the U.S. This analysis establishes a benchmark of data that Sarasota County can use to evaluate the effectiveness of public policy concerning urban forestry management in the future.

Two separate but parallel analyses were performed to evaluate the changes, functions, and values of the vegetation in Sarasota County. The first analysis involved a regional vegetation mapping and trend analysis using satellite imagery. The second analysis involved a small area mapping and modeling effort focusing on the urbanized portion of the County. The resulting data from this second "local" analysis were used to develop estimates of air quality benefits and energy cost savings provided by vegetation canopy. To address the benefits of vegetation coverage on stormwater runoff, a detailed literature review of existing studies related to rainfall interception by tree canopies was performed. Based on a review of this literature (primarily from studies in California), rainfall interception ranges from about 5% to nearly 100% with an average of approximately 11%. The variability in interception is mainly due to differences in the intensity (amount and duration) of precipitation, humidity, temperature, and tree species (leaf area, branch structure, canopy cover). The percent of rainfall intercepted is generally greatest for small short duration storms and with trees having large leaf areas.

Between 1975 and 1986, overall vegetation cover decreased from 71% of total land cover to 47% of total land cover representing a net decrease of 33%. Significant development and land clearing took place in northern, western, and southeastern Sarasota County during this period. However, between 1986 and 1993, a 4% gain in vegetation canopy was observed, possibly due to the regrowth of vegetation that was originally cleared for development in the North Port area, as well as several developments throughout the County that had been replanted with vegetation after construction. Between 1993 and 2002, total canopy coverage was reduced from approximately 181,077 acres to 173,907 acres which represents a net 4% loss in vegetation canopy. Based on the satellite imagery, this loss occurs in several areas throughout the County due to clearing of vegetation in the eastern and southern portions of the County for cattle grazing and other agricultural purposes along with continued residential development both west and east of I-75. Gains in canopy were also observed throughout the County, including some of the previously cleared agricultural areas in the eastern part of the County.

A total of 1,674 trees representing 68 species were inventoried during the local analysis field data collection surveys within the County. Palms (sabal, queen, Washingtonia) were the most abundant species in high density residential land uses while slash pines and sabal palms were abundant in open land areas. Live oak, Australian pine, and sabal palms were the most predominant species at recreational lands. Queen palm and live oak trees were most prevalent at medium density residential land uses. Sabal palm, slash pine, laurel and live oak trees were the most abundant species in low density residential land uses. The average percentage of native species (by abundance) for all sites was approximately 50%. This value is similar to the 46% reported in the City of Tampa (Campbell and Landry, 1998). In addition, laurel oak which is a relatively short-lived species (~100 years) represented 10% of species found within the urban sites. In the future, these trees may represent a significant canopy loss in the urban areas as they naturally decline.

The combined economic benefits calculated using the CITYgreen model, estimates the total economic value of the vegetation canopy within urban land uses in Sarasota County at approximately $8 million per year. This estimate is based on extrapolation of the average cost savings associated with air pollution controls and residential energy (air cooling) costs, for each of six urban land use types evaluated multiplied by the number of acres of each land use type which currently exists in Sarasota County. Based on these calculations, open land provides a significant economic benefit to the County in terms of air pollution removal and is likely to provide similar benefits for stormwater runoff reduction. The economic benefits provided by this land use type are significant, because nearly 26,000 acres of this land use remains in the County. However, it should be noted that the values used to generate the cost savings values for this land use were based on only three sites, including two sites in the North Port area which are heavily canopied. These sites were originally platted and cleared for development in the 1970s (hence their designation as "open land") but were never built out. In concert with existing land development codes and tree protection ordinances, implementation of more innovative designs to protect existing tree canopies in these areas should be considered since the greatest economic costs for air and water quality protection are represented by this land use type.

The existing vegetation canopy in medium density residential land use also provides a significant economic benefit to Sarasota County. Many older neighborhoods are becoming more heavily canopied as a result of decades of tree growth since their original development. Tree planting programs may also have a significant effect on improving air and water quality in commercial and recreational areas, however, these effects will likely take several years to be realized.

Several recommendations can be made based on the analysis of the vegetation canopy coverage and local site analysis performed in this study:

1. ***Evaluation of Sarasota County Tree Protection Policies*** - The vegetation and tree canopy coverages calculated from this study should be used to evaluate key public policies such as the County's Comprehensive Plan and future tree protection ordinances. As demonstrated in this study and many others across the U.S., the principle ecological and economic benefits are directly related to the percentage of canopy cover and not necessarily numbers of individual trees. Canopy cover goals should be set by land use type within the comprehensive plan and local development ordinances. Sarasota County implemented its tree protection policy in 1983 through ordinance no. 83-44. This ordinance was amended in 1995, 1998, and 2002. The October 2002 amendment was the adoption of a program for the designation and preservation of grand trees. Grand trees were determined to be an important component of the urban forest, and have unique and intrinsic values to the general public due to their size, age, and ecological value. The apparent effects of the County's tree protection program are the stabilization of vegetation canopy coverage during the past two decades. However, future re-evaluations of vegetation canopy cover every three to five years should be performed using the same methodology presented in this report to monitor the effects of existing tree protection programs, especially in areas east of I-75 where the greatest development pressures are likely to occur.

2. ***Conduct Additional Research in Southwest Florida to Determine Rainfall Interception by Native Tree Species*** – Several studies evaluating tree canopy cover and rainfall interception have been completed recently, however, none were found that specifically addressed tree species or meteorological conditions unique to southwest Florida. Additional research in this area would be extremely useful in assessing economic benefits of the vegetation/tree canopy cover for reducing/attenuating stormwater runoff in Sarasota County and other areas in the region.

3. ***Implementation of Strategic Tree Planting Programs for Stormwater and Air Quality Improvement*** - Based on the results of previous studies evaluating the mechanism for rainfall interception by tree canopy, future tree plantings in urban areas should target residential areas, open lands and impervious surface areas (e.g., roads and parking lots). Rainfall interception by the tree canopy will have the greatest effect when impervious surfaces are directly shaded/covered by the canopy since nearly all of the rainfall falling on impervious areas runs off into drainage systems. The County's Public Works division has already begun implementing a street tree planting program where tree plantings are incorporated into the medians and shoulders of new roadway improvement projects. Selection of tree species which provide a large tree canopy, high leaf to area ratios, are leafed out year round or only briefly deciduous, and which can withstand pruning and disturbance should provide the greatest benefit to reducing stormwater runoff and pollutant loads to receiving waters. A thorough analysis to identify optimal tree planting scenarios with respect to this ongoing County program should be performed – the expected benefits could be calculated using the results of the additional rainfall interception research as proposed above.

   Tree planting efforts should also target existing residential areas, possibly by providing subsidized trees to individual property owners. Since private homeowners will be responsible for maintaining subsidized trees, the cost and risk to grow out individual trees to maturity is relatively small while the economic and environmental benefits can be significant given the large area of the County which is occupied by residential development.

4. ***Create a High Resolution GIS layer of Sarasota County's Tree Canopy*** – Using existing technology and aerial photography of 1 meter resolution or better, a detailed GIS layer of the tree canopy should be created. This layer could be used for a variety of planning applications including development of strategic tree planting plans (e.g, targeting areas of greatest stormwater/water quality benefits) and evaluation of the effectiveness of the current tree protection ordinance.

5. ***Create Incentives for Homeowners to Plant Preferred Tree Species*** – Many communities offer a tree rebate program as incentive for homeowners to plant approved tree species in residential landscapes. Based on the results of this study, it appears that such a program would greatly benefit the urban environment in Sarasota County.

6. ***Communicate the Results of this Study*** – The results of this study should be shared with the general public and especially residential and commercial developers and agencies which regulate development. Communication could occur through brochures, information posted on the County's website, or public meetings. Brochures could be distributed to homeowners that highlight the results of this study and describe optimal planting schemes, vegetation species, and any incentive programs that developed to increase residential plantings. Through increased dialogue and feedback from the public, it may be possible to develop innovative designs or techniques that minimize vegetation canopy loss while still maintaining affordable and sustainable developments.

Forward and Acknowledgments

Forward

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Contents

Contents

1.0 Introduction

Sarasota County covers a land area of approximately 370,000 acres or 580 square miles. Before widespread colonization by European settlers, the County was characterized by a variety of natural vegetation communities including pine flatwoods, hardwood hammocks, scrub, prairies, fresh and saltwater marshes, mangrove forests, and seagrass beds. Since these different vegetation communities adapt to varying soils conditions, a historical representation of vegetation coverage in the County was created by using National Resource Conservation Service (NRCS) soils survey maps. **Figure 1-1** depicts what was likely the vegetation distribution throughout the County before human settlement.

Although large portions of the County are still comprised of native vegetation cover, urban and agricultural development have had a significant impact on these natural systems. This has resulted in changes in both wetland and upland vegetation over the past century.

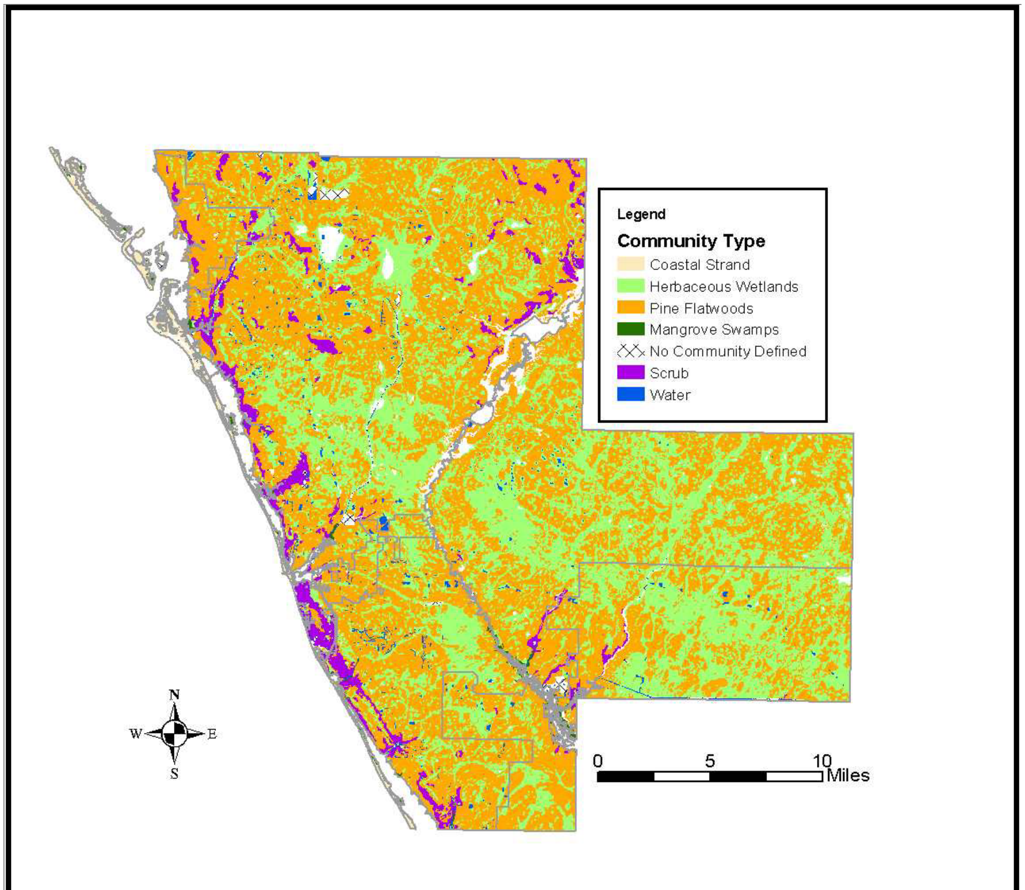


Figure 1-1. Historical vegetation communities in Sarasota County predicted by soils maps (source: SWFWMD and NRCS).

The effects of urbanization and development have had a significant effect on water quantity and quality in Sarasota County. During a storm, rain falls on the earth's surface and is either absorbed into the ground or flows over the land into streams, lakes, or drainage features such as ditches or canals. Sensitive ecosystems such as lakes, streams, creeks, wetlands, and estuaries have historically been impacted by untreated stormwater runoff and habitat loss. This can have an adverse effect on water quality and biological processes such as increases in pollutant loads (e.g., nutrients), increases in aquatic primary productivity (leading to algal blooms), declines in water clarity, reductions in the growth of seagrasses and other aquatic vegetation, and changes/declines in wildlife usage.

The loss of natural vegetation and streamside buffers along natural creeks affects the timing, duration, and quality and quantity of stormwater runoff. Urban development typically results in the creation of impervious surfaces (e.g., roads, rooftops, parking lots, sidewalks) which have significant effects on runoff. These effects include:

- higher and more rapid peak surface discharge than pre-development levels;
- increased surface runoff volume during storm events;
- reduced evapotranspiration;
- reduced infiltration and groundwater recharge;
- reduced base flow rate and volume;
- reduced interception and depression storage;
- reduced time needed for surface runoff to enter the receiving waterbody (i.e., shorter time of concentration);
- increased frequency of surface runoff;
- increase in erosion and contaminants discharged to receiving waterbodies; and
- increased water temperature in surface runoff.

Figure 1-2 illustrates the differences in flow rates from both an individual storm event (left graph) and seasonal (right graph) perspective with respect to developed versus undeveloped conditions in a watershed. Although a number of stormwater management controls have been developed to capture, attenuate/store, and treat runoff, enhancement of the urban forest is often overlooked as a cost-effective best management practice for stormwater management. Tree/vegetation canopies can attenuate rainfall through interception, evapotranspiration, and sequestration in the root/soil matrix zone. The roots and soil ecosystem beneath the tree canopy can perform filtration and bioremediation of stormwater and provide groundwater recharge.

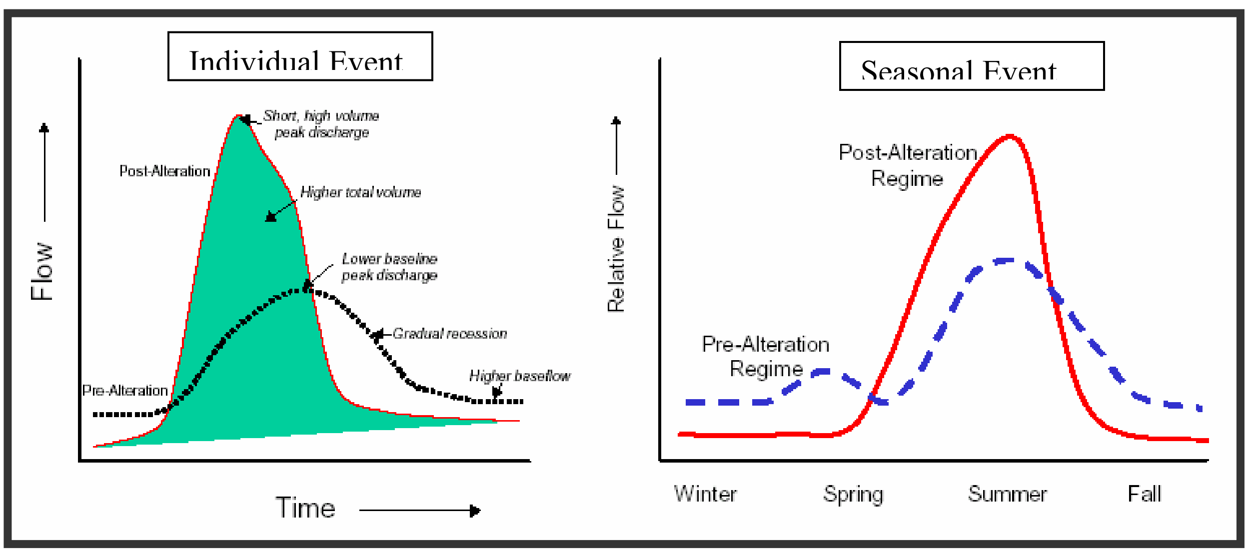


Figure 1-2. Hydrographs depicting typical changes in flow over time in developed versus undeveloped site conditions. (From Federal Interagency Stream Restoration Working Group, 1998)

1.0 Introduction

As urban areas continue to expand nationwide, it is becoming more important for local governments to evaluate the condition of the urban forests that occur within their political boundaries. The number of people moving to the State of Florida is increasing, creating a significant strain on natural resources. This strain has historically been exacerbated along coastal areas which are often considered the most desirable areas to live and recreate. At the same time that urban forests are under continued pressure they are increasingly being recognized as a form of infrastructure that can provide many ecosystem services to local communities. Previous studies have shown that urban trees reduce stormwater runoff (Xiao and McPherson, 2002), ameliorate certain air pollutants (Nowak et al., 1994a), sequester carbon (Nowak 200), reduce residential and commercial energy use through shading (McPherson, 1998), and improve property values (Anderson and Cordell, 1988).

More recently, suburban development has continued to expand inland where large tracts of land still exist. These areas are logistically more feasible for the construction of large residential developments. However, this type of development has led to clearing of existing vegetation since current regulatory requirements to reduce structural flooding often involve placing large volumes of fill at a site prior to home construction. This results in land clearing and then replanting the raised home site with smaller tree and shrub species after construction. To reduce these impacts, Sarasota County has developed land development ordinances and rules which reduce the loss of important forest ecosystems while still allowing a sustainable approach to the increasing demand for new development.

This study was performed for the Sarasota County Forestry Division to evaluate large scale (County-wide) changes in vegetation coverage over the past 30 years and also to evaluate the functions and values of the urban forest with respect to stormwater runoff, energy savings, and air quality. The results of this study were compared to other similar studies which have been performed throughout the U.S. The analysis performed for this study also establishes a benchmark of data that Sarasota County can use to evaluate the effectiveness of public policy concerning urban forestry management in the future.

Specific objectives for this project were to:

- Quantify the change in overall vegetation coverage in Sarasota County from 1975-2002;
- Assess the values of the vegetation coverage in urbanized areas with respect to air quality, energy costs, and stormwater interception;
- Compare the results of this study with other areas of the U.S. which have performed similar evaluations including the City of Tampa; and
- Provide recommendations for enhancing vegetation coverage in the County.

2.0 Methods and Materials

Two separate but parallel analyses were performed to evaluate the changes, functions, and values of the vegetation in Sarasota County. The first analysis involved a regional vegetation mapping and trend analysis using satellite imagery. Vegetation included both tree and shrub species (e.g. palmetto, wax myrtle) but did not included grasses or prairie areas. The second analysis involved a small area mapping and modeling effort focusing on the urbanized portion of the County. The resulting data from this second "local" analysis were used to develop estimates of air quality benefits and energy cost savings provided by vegetation canopies.

Landscape features, such as vegetation or forest canopy cover, can be represented in one of two ways: raster or vector. Raster data are based on cells or pixels to depict a given feature or habitat type. Depending upon the pixel size of a raster map image, a rasterized tree, for example, is generally less accurate than a vectorized tree. Although vector data is more accurate, it is time consuming to prepare over a large area. Therefore, raster data was used for the regional analysis. Vector data sets delineate the boundaries or locations of land features such points, lines, and polygons that could represent vegetation canopy or building outlines. Vector representations are a highly accurate depiction of the landscape and were used to develop the small area or "local" analysis.

Regional Analysis

In 1972, the U.S. launched the Earth Resources Technology Satellite (Landsat 1) for experimental global coverage of the Earth's land forms. Landsats 2 through 5 were launched in 1975, 1978, 1982, and 1984. Data from these satellites are collected by sensors that measure a range of wavelengths of electromagnetic energy reflected or emitted from the Earth. The data are transmitted back to Earth, where they are processed and stored. Landsats 1 through 5 carried a multispectral scanner (MSS) that collected data simultaneously from four broad bands of the electromagnetic spectrum, from visible green through near-infrared wavelengths. MSS images have a resolution of about 80 meters (260 feet) and each image is cataloged as a "scene"; the approximate scene size is 185 x 170 kilometers (115 x 106 miles). A thematic mapper (TM) sensor was carried on Landsats 4 and 5, in addition to the MSS, and has a resolution of about 30 meters (98 feet) per pixel. The TM sensor also records a greater number of bands than the MSS, yielding more detailed spectral information. Landsats 4 and 5 orbit from north to south over the Equator at an altitude of 705 kilometers (438 miles) each day at about 10 a.m., and their orbits repeat coverage of the Earth, allowing the detection of change. Specifications of this satellite imagery are presented in **Table 2-1**.

Landsat imagery was obtained from the U.S. Geological Survey (USGS) for the periods 1975, 1986, 1993, and 2002 to evaluate changes in vegetation coverage by decade (approximately) as well as the location and extent of urbanized areas (buildings and roads) and water features (**Figure 2-1**). The MSS imagery was used for 1975 since this was the only type of satellite data available prior to the 1980s. Thematic mapper (TM) images were used for the years 1986, 1993, and 2002. A number of criteria had to be met for image selection to ensure meteorological and atmospheric compatibility between images. Images were selected based upon phenological stability (leaf-out conditions), lowest percent cloud cover, minimal differences in precipitation, and spectral compatibility. In southwest Florida, the time frame which is optimal for these combined criteria is late spring. In addition all of the images must be acquired by the satellite during approximately the same time period each year. As shown in **Figure 2-1** the images were selected in the (March-April) time frame. Leica Geosystems' Image Analysis for ArcGIS was used to classify the satellite imagery using the Normalized Difference Vegetation Index (NDVI). The NDVI calculation for the MSS and TM satellite data is as follows:

$$NDVI = NIR-R/(NIR+R)*100$$

where NIR = near infrared band, and R = red band

2.0 Methods and Materials

For each image, the classified NDVI data was converted to an Arc/Info GRID layer and classified/ recoded to represent three land cover classes (water, open land, and vegetation cover). Open land was characterized as those areas devoid of trees and shrubs (e.g., roads, parking lots, roof tops, grassed fields, prairies, etc.). The classified images were then saved as ERDAS Imagine (img) layer files for further analyses. These layers were overlaid with the Sarasota County boundary obtained from Sarasota County's Geomatics section. The img file was modified to remove features outside of the County boundary using ArcGIS Spatial Analyst. Percent canopy and acreage calculations were then calculated using Leica Geosystems' Image Analysis and ArcGIS Spatial Analyst extensions.

Table 2-1. Specifications for Landsat imagery.

	Landsats 1-3	Landsats 4-5	Wavelength (micrometers)	Resolution (meters)
Multispectral Scanner (MSS)	Band 4	Band 1	0.5-0.6	80
	Band 5	Band 2	0.6-0.7	80
	Band 6	Band 3	0.7-0.8	80
	Band 7	Band 4	0.8-1.1	80
	Band 8 (Landsat 3 only)	not available	10.4-12.6	237

	Landsats 4-5	Wavelength (micrometers)	Resolution (meters)
Thematic Mapper (TM)	Band 1	0.45-0.52	30
	Band 2	0.52-0.60	30
	Band 3	0.63-0.69	30
	Band 4	0.76-0.90	30
	Band 5	1.55-1.75	30
	Band 6	10.40-12.50	120
	Band 7	2.08-2.35	30

Local Analysis

Urban forests provide benefits to the human population by reducing air pollution, intercepting and slowing the rate of stormwater runoff, and conserving energy by providing shade. These benefits can be calculated on a monetary basis, which can help local governments assess the values of urban forests with regard to public policies and future budget planning. The software package CITYgreen was developed by the non-profit organization American Forests to assist communities in calculating the economic value of these ecological services from the urban forest canopy. CITYgreen calculates these benefits using a series of previously developed air pollution and stormwater models which run as an ArcView GIS extension. Detailed descriptions of the various modeling components are provided in **Appendix A**. These models calculate the economic and quantitative values for the following parameters based on local mapping of vegetation canopy areas with respect to vegetation species and size, buildings and impervious surfaces:

- **Air Pollution Removal** – Urban forests absorb and filter out nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), carbon monoxide (CO), and particulate matter less than 10 microns (PM_{10}) in their leaves. CITYgreen estimates the annual air pollution removal rate of trees within a defined study area for the above pollutants. To calculate the dollar value for these pollutants, the model estimates "externality" costs, or indirect costs borne by society for rising health care expenditures and reduced tourism revenue. The actual externality cost for various air pollutants is set by the State Public Services Commission in each state. The model is based on a methodology developed by the United States Forest Service (McPherson, et. al, 1994).

2.0 Methods and Materials

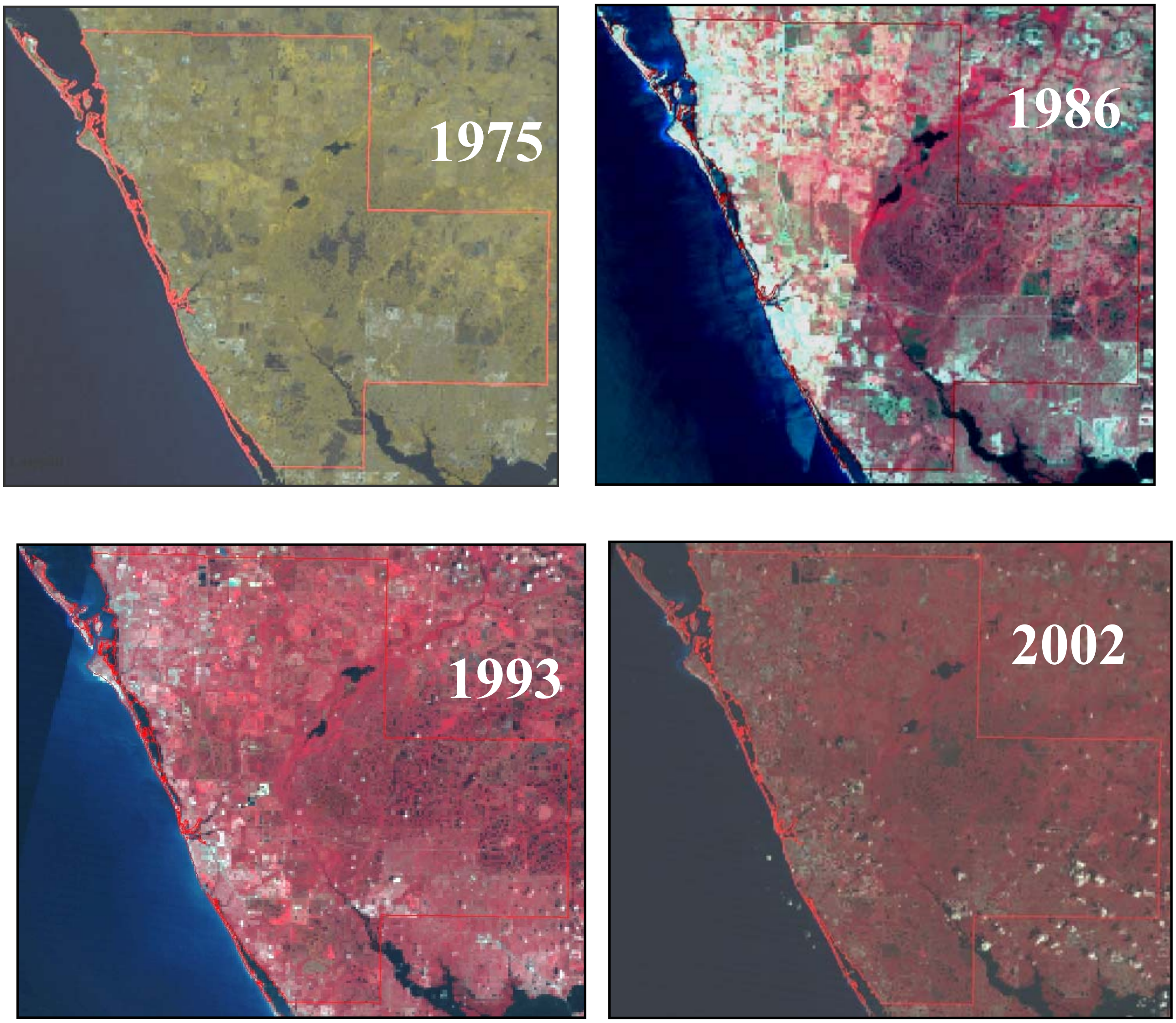


Figure 2-1. Landsat imagery for 1975, 1986, 1993, and 2002 for Sarasota County.

- **Carbon Storage and Sequestration** – Trees and other vegetation can remove carbon dioxide from the atmosphere through their leaves and store carbon in their biomass. Approximately 50% of the dry weight of a tree is carbon (American Forests, 2002). CITYgreen estimates the carbon storage capacity and carbon sequestration rates of trees within a defined study area based on the size and age of observed tree species.

- **Stormwater Control** (changes in peak flows and storage volumes) – Sarasota County's stormwater management program has a comprehensive stormwater and drainage control program and has constructed hundreds of projects to reduce flooding throughout the County. By reducing peak flows that occur during and immediately following a storm event, the urban vegetation canopy is often greatly under appreciated, but is an integral component of a successful stormwater management system. Although CITYgreen has a modeling feature to address stormwater runoff, reviews by County staff (S. Suau, personal communication) indicated that the models used in this analysis were inadequate to accurately describe the specific effects of vegetation canopy on stormwater attenuation. To address the benefits of vegetation coverage on stormwater runoff, a detailed review and discussion of existing studies related to rainfall interception by tree canopies were performed.

- **Residential Cooling Effects** – The USDA Forest Service and other agencies have shown that trees strategically planted to shade homes can reduce air conditioning costs. CITYgreen assigns energy ratings to trees using their location, species, and height. Based on local climate and cooling costs, CITYgreen can estimate the dollar value of the direct shading benefits that trees provide to buildings. In addition to carbon storage and sequestration, trees provide a secondary carbon-related benefit. Since less energy is needed for summer cooling, local power plants do not need to produce as much electricity and, thus emit less pollution, including carbon. Based on the total energy savings for an area, CITYgreen also calculates the amount of avoided utility-based carbon emissions.

For the local analysis, several study sites were identified based on an analysis of existing land use categories found within Sarasota County. Since the results of this analysis are extrapolated to describe the remainder of the County, selection of study sites representative of the predominant urban land uses was extremely important. It should be noted that discussions regarding land use are based on the Florida Department of Transportation's (FDOT) Florida Land Use and Cover Classification System (FLUCCS). This classification system is similar to the County's Comprehensive Plan (Apoxsee) land use designations; however, certain specific land use classes in FLUCCS are less descriptive than Apoxsee. The term "urban" in this study includes developed land uses such as residential, commercial, institutional, utilities, transportation, industrial, recreational, and open land (disturbed/cleared of vegetation). It does not include agricultural or natural land use types.

Predominant land use categories were calculated by clipping the Southwest Florida Water Management District 1999 land use map layer to the Sarasota County boundary and then calculating the areas of each land use type within the County (**Figure 2-2**). Based on this analysis, the predominant land use was natural land (uplands and wetlands) which represents approximately 51% of the total land area in the County (**Table 2-2**). Most of this land use type occurs in the east and central portions of the County, mainly east of I-75. The second highest percentage was cropland and pastureland at approximately 13%. Urban land uses (residential, commercial, industrial, transportation) make up the remainder of the County's land use (32%) followed by a relatively small percentage of other mixed land use types (4%). The urban land uses are most concentrated along the coastline in the northwestern and southwestern portions of the County, mainly within the City of Sarasota, City of Venice, and Englewood. Six urban land use categories (highlighted in yellow in **Table 2-2**) comprise approximately 29% of the total land use and the majority (approximately 84%) of the urbanized or developed land uses in the County. As a result of this analysis, residential low density, residential medium density, residential high density, open land, recreational, and commercial land uses were selected as candidate land use types for the local analysis. This is consistent with other communities that have conducted similar studies using the CITYgreen methodology (Campbell and Landry, 1998).

To select individual areas for the local analysis, the 2000 U.S. Census Block information was obtained and overlaid onto the 1999 land use maps. The intersect function in ArcGIS was used to select those census blocks that were comprised by at least 80% or greater of a single land use type. A map showing this information is presented in **Figure 2-3**. This information was further refined to identify the year in which a particular census block was developed by extracting the construction date of structures within the parcels of a census block using the Sarasota County property appraiser's database. Dates of construction were used to assess the age of a particular study site to determine if building practices or the amount of time elapsed since construction had an effect on vegetation cover. The resulting map of this information is presented in **Figure 2-4**.

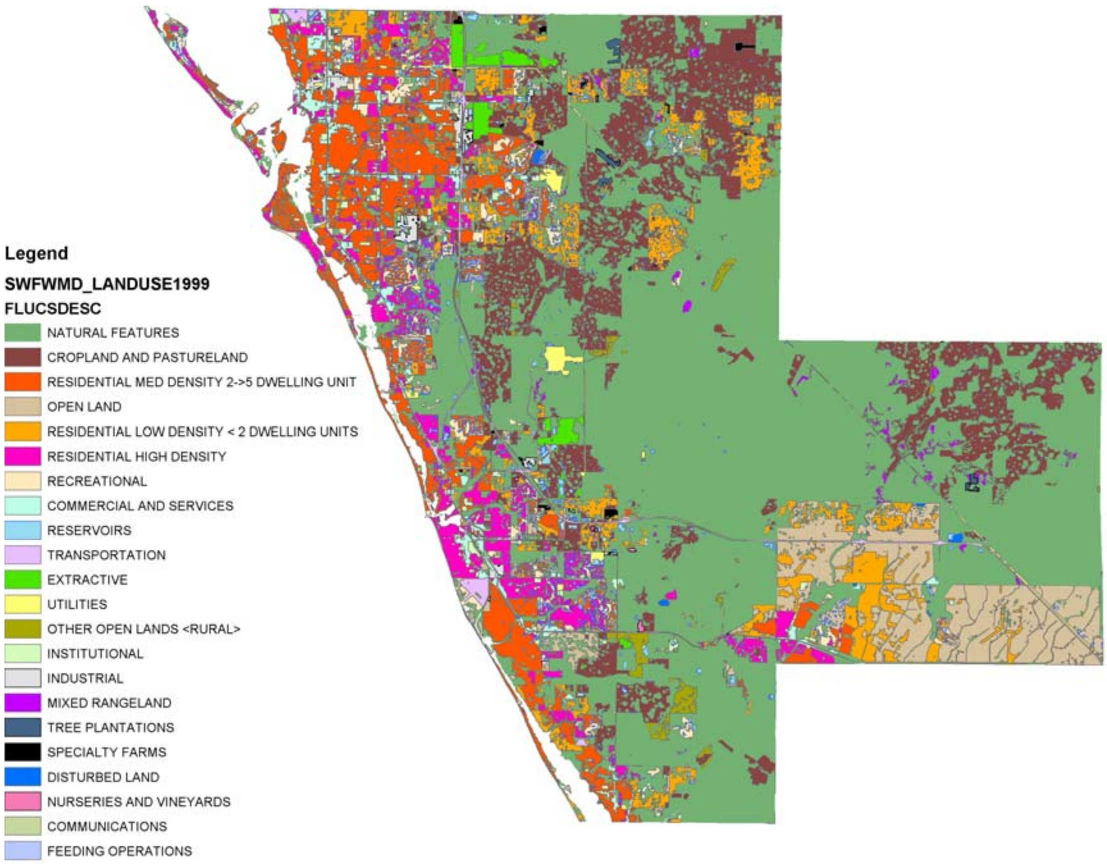


Figure 2-2. SWFWMD 1999 land use map for Sarasota County.

Using this series of maps, several sites were randomly selected for the local analysis based on the six land use types which comprise the majority of urban land use types in the County. Three replicates of each of the six land use types were selected along with three additional sites that served as replacement sites in the event that the land use category had changed for a given census block since the 1999 land use mapping had been performed by SWFWMD. This resulted in a total of 21 local analysis sites which were distributed throughout the County (**Figure 2-5**). By having three replicates of each land use type, an averaging of similar land use types could be performed thereby reducing the potential risk of selecting a unique or unrepresentative site and extrapolating that information throughout the remainder of the County. The final list of 18 sites selected for analysis were sites 1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 14, 15, 16, 17, 18, 19, and 20. Based on initial reviews of each site, each appeared to be representative of the land use type designated for that site. A list of the sites, the land use type each represents, area surveyed, and the year structures were built on the site are presented in **Table 2-3**.

Table 2-2. Land use categories within Sarasota County based on 1999 SWFWMD FLUCCS map data. Predominant urbanized land uses are highlighted in yellow.

Land Use Category (FLUCFS)	Acre	% of total Area
NATURAL FEATURES	189,816	51.2
CROPLAND AND PASTURELAND	47,256	12.7
RESIDENTIAL MED DENSITY 2->5 DWELLING UNIT	29,512	8.0
OPEN LAND	25,902	7.0
RESIDENTIAL LOW DENSITY < 2 DWELLING UNITS	21,664	5.8
RESIDENTIAL HIGH DENSITY	16,462	4.4
RECREATIONAL	8,004	2.2
COMMERCIAL AND SERVICES	6,104	1.6
RESERVOIRS	6,045	1.6
TRANSPORTATION	4,285	1.2
EXTRACTIVE	2,900	0.8
UTILITIES	2,892	0.8
OTHER OPEN LANDS <RURAL>	2,650	0.7
INSTITUTIONAL	2,131	0.6
INDUSTRIAL	1,741	0.5
MIXED RANGELAND	1,690	0.5
TREE PLANTATIONS	528	0.1
SPECIALTY FARMS	492	0.1
DISTURBED LAND	390	0.1
NURSERIES AND VINEYARDS	346	0.1
COMMUNICATIONS	86	0.023
FEEDING OPERATIONS	13	0.004

For each site, digital color aerial photographs acquired by Sarasota County in 2001 were used to digitize vegetation canopy, roads, and building features which resulted in a vector layer of site-specific data (i.e., polygons). Each of the selected sites are presented in **Appendix B**. Maps of these areas were then printed and taken in the field for verification and collection of additional data at each site including:

- Location and extent of all impervious surfaces
- Identification of each vegetation canopy species within the study site
- The trunk diameter at breast height (dbh) otherwise known as the diameter, in inches, at 4 ½ feet above ground
- The growing condition of trees and other woody vegetation such as the substrate in which it was growing within (impervious substrate, natural forest, grass/turf)
- Height class (<25 feet, 25-45 feet, >45 feet)

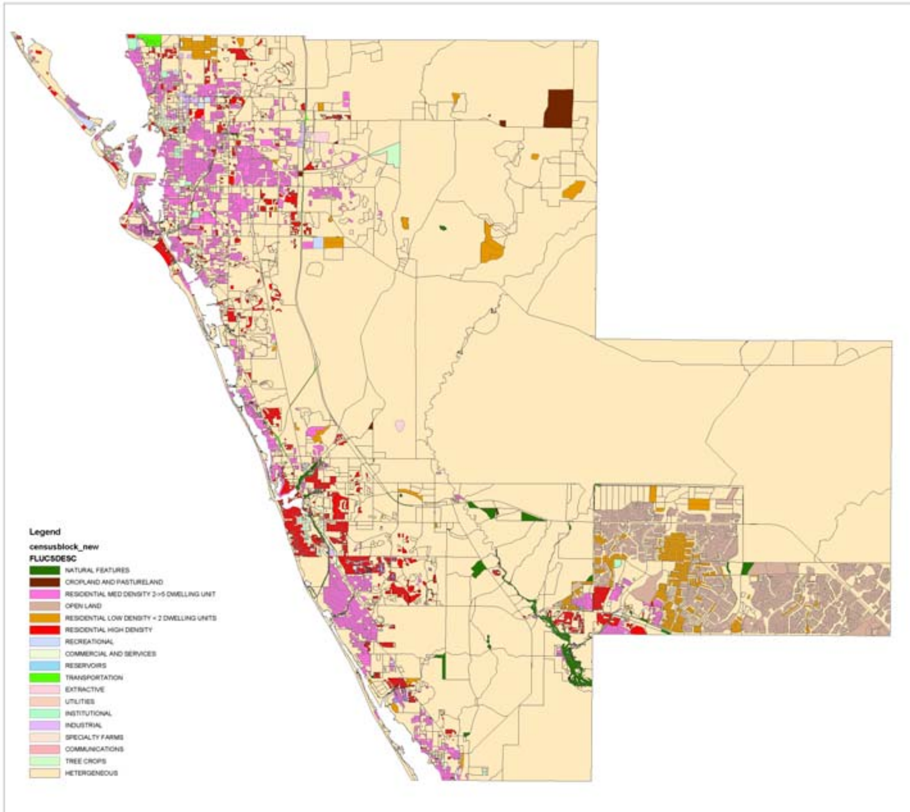


Figure 2-3. U.S. Census Blocks comprised of single land use categories.

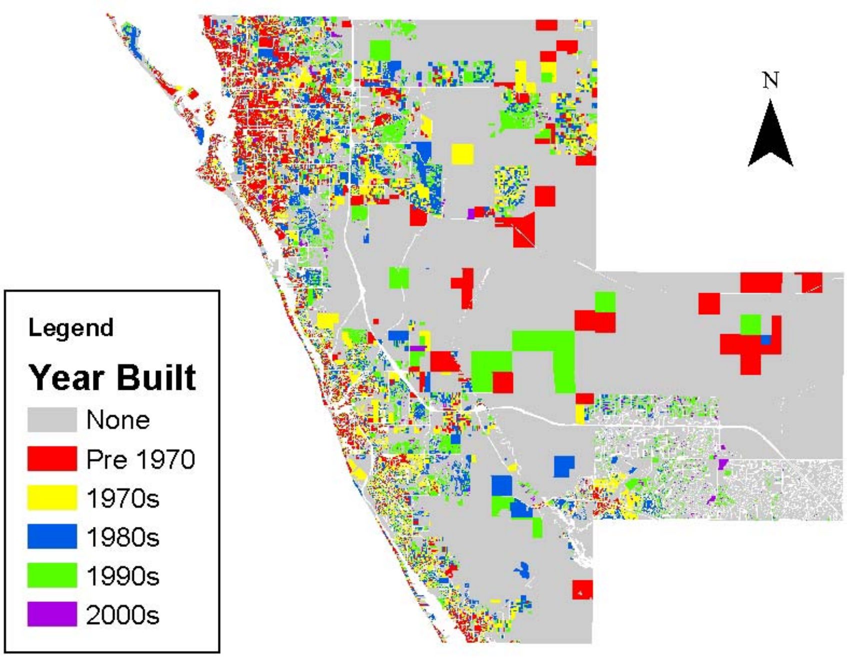


Figure 2-4. Average age of building structures based on Sarasota County Property Appraiser's database.

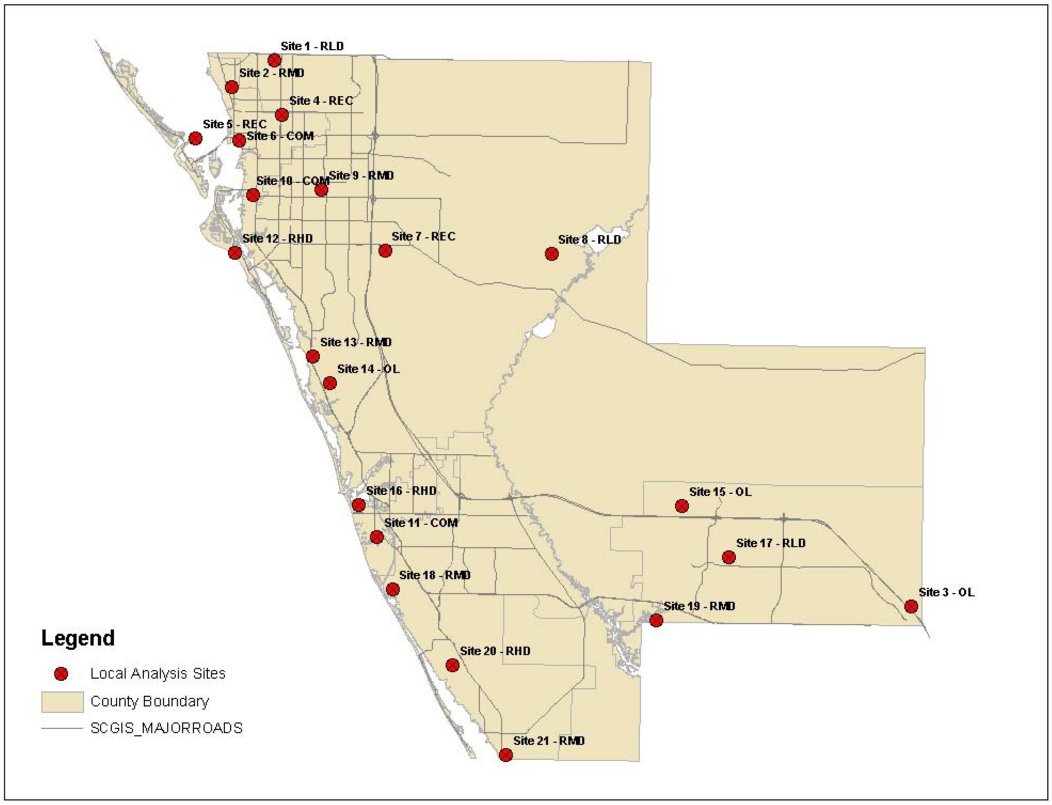


Figure 2-5. Sites selected for local analysis (RLD = residential low density, RMD = residential medium density, RHD = residential high density, OL = open land, COM = commercial, REC = recreational).

Table 2-3. Site descriptions for the local analysis.

Site	Type	Area (ac)	Year Built Out
1	Residential Low Density	9.87	Pre 1970 to 1970
2	Residential Med Density	4.23	Pre 1970 to 1970
3	Open Land	4.88	n/a
4	Recreational	11.38	n/a
5	Recreational	4.87	n/a
6	Commercial	2.24	Pre 1970
7	Recreational	1.7	n/a
8	Residential Low Density	16.3	1970 to 1980
10	Commercial	14.48	Pre 1970 to 1990
11	Commercial	1.02	1990
12	Residential High Density	4.79	Pre 1970
14	Open Land	0.81	n/a
15	Open Land	6.11	n/a
16	Residential High Density	5.05	Pre 1970 to 1990
17	Residential Low Density	1.66	Pre 1970 to 1990
18	Residential Med Density	6.05	Pre 1970 to 2000
19	Residential Med Density	5.03	1980
20	Residential High Density	6.65	Pre 1970 to 1990

2.0 Methods and Materials

Field sampling teams comprised of trained botanists/biologists visited each study site between August and October of 2003. The digitized features were then adjusted according to the field observations. The positions and locations of smaller vegetation that was located beneath larger trees were adjusted and/or added.

Once the small area maps were completed and verified in the field, this information was updated in the original ArcView shapefiles created prior to mapping. Each of the features delineated was then assigned several characteristics (tree species, height, condition, etc.) and entered into the attribute table in ArcView. The CITYgreen model was then run using the updated and attributed information for each of the 18 sites.

CITYgreen Analyses

The CITYgreen software was designed to model the benefits of tree/vegetation canopy using previously developed models and analytical calculations from the U.S. Department of Agriculture, Lawrence Berkeley Lab, and others. Included in the software package are tools to model energy conservation, air pollution removal, carbon storage and sequestration, and wildlife benefits. As mentioned previously, the stormwater runoff module of the CityGreen software package was not used to assess economic benefits due to potential inaccuracies in model results.

Air Pollution Removal Modeling

The model used to calculate air pollution removal was based on a methodology developed by the United States Forest Service (McPherson et al., 1994). The model uses average yearly pollutant flux (grams of pollutants per square centimeter per second) based on studies conducted in Chicago, Austin, Baltimore, and Milwaukee in order to determine total pollutant removal. Because rate of uptake may differ between these four cities and Sarasota County, pollutant removal statistics should be viewed as estimates only.

Carbon Storage and Sequestration Modeling

Trees and other vegetation process carbon dioxide and produce oxygen. As part of this process, trees store carbon throughout their life history. Young, rapidly growing trees store carbon faster than older, slower growing trees (American Forests, 2002). Carbon storage and sequestration rates for each study site were calculated based on the total area of the vegetation canopy at the site multiplied by a carbon storage (or sequestration) constant based on the age of the entire forest population at the site (Nowak and Rowntree 1993). Tree age was estimated based on site-specific data collected for tree diameter and height.

Energy Conservation Modeling

The energy conservation model included in the CITYgreen application estimated the kilowatt-hour savings resulting from direct shading of buildings, air conditioners and windows by vegetation canopy (Forests 1997b). Energy ratings were assigned (by the model) to each vegetation species and then multiplied by an energy savings constant developed based on results of two recent studies of the urban forest ecosystem (McPherson, Nowak, and Rowntree 1994) and (McPherson, Sacamano, and Wensman 1993). Included in the model was an estimate of the average cooling costs for residential homes in Sarasota County, $329.94/year (Florida Power and Light, 2003). Information collected during field sampling was entered into the ArcView CITYgreen extension, including the detailed vegetation information and all land cover polygon corrections and additions (i.e. trees, buildings, air conditioners and windows, grasslands, and impervious surface). In order for all CITYgreen analyses to function properly, all land cover polygons (including vegetation/trees) could not extend beyond the study site boundary polygon and were appropriately cropped. After all data was entered, CITYgreen was used to calculate general statistics related to percent coverage of land cover types, vegetation species diversity, and vegetation health and population information for each study site.

Finally, CITYgreen analyses were used to determine carbon storage and sequestration rates, annual pollution (Ozone (O_3), Sulfur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Particulate Matter (PM_{10}), and Carbon Monoxide (CO)) removal rates for each study site. Because the energy savings models included in the CITYgreen application are based on single story residential homes (American Forests, 1997b), energy savings resulting from vegetation canopy shading were calculated for single-family residential study sites only.

Statistical Analyses

All data resulting from CITYgreen statistical summaries and models were analyzed using Microsoft Excel (Microsoft 1997). Regression analyses were based on a 95% confidence level. Results were extrapolated using simple averages or weighted averages (weighted by land-use category) to obtain estimated land cover, pollution reduction, and other values for Sarasota County.

3.0 Results and Discussion

Regional Analysis

Countywide Temporal Change in Vegetation Canopy Coverage

The results of the satellite imagery analysis of vegetation canopy cover are illustrated in **Figure 3-1** and summarized in **Table 3-1**. A more detailed breakdown of the satellite imagery analysis results can be found in **Appendix C**. **Table 3-1** shows the cover (in acres) of the three land cover categories that were used to differentiate the vegetation canopy from land and water features. Analyzing the change in canopy coverage between 1975 and 1986, overall canopy cover decreased from representing 71% of total landcover to 47% of total landcover. This represents a net decrease of 33% (**Figure 3-2**). Significant development and land clearing took place in northern, western, and southeastern Sarasota County during this period. The effects of urban and agricultural development, and probably to a lesser degree the preceding drought conditions, resulted in a loss of approximately 87,000 acres of vegetation canopy.

Table 3-1. Changes in land cover between 1975 and 2002 in Sarasota County based on imagery analysis.

	Cover (acres)				%
YEAR	OPEN LAND	VEG.	WATER	Total	Trees
1975	107,537	261,811	732	370,081	71%
1986	192,963	174,905	2,373	370,240	47%
1993	187,148	181,077	2,032	370,257	49%
2002	191,694	173,907	4,653	370,254	47%

The total number of acres for each year differs due to slight differences in the numbers of pixels occurring in the satellite imagery during each of the four decades used in the analysis. These minor inaccuracies contribute less than 0.05% of the total coverage.

A large increase in water features also occurred during the period between 1975 and 1986. This is partially due to the construction of I-75 which required fill for interchanges that resulted in numerous large borrow pits. In addition, a portion of the coastline that was beach/land in the 1970s became water features during the 1980s. This is likely due to changes in the coastline due to erosion or sand migration. **Figure 3-3** depicts the changes in vegetation canopy coverage with respect to existing land uses in 1999. This chart gives a general indication of the causes of vegetation canopy loss by land conversion activities. What is currently cropland and pastureland was historically represented by a greater percentage of vegetation canopy cover. The same trends can be seen for areas that are now low, medium, and high density residential development and open land.

However, between 1986 and 1993, a 4% gain in vegetation canopy was observed, possibly due to the regrowth of vegetation that was originally cleared for development in the North Port area, as well as several developments throughout the County that had been replanted with trees and other vegetation after construction. Some older neighborhoods in the City of Sarasota and Venice also exhibited very patchy gains in vegetation canopy. The County's Tree Protection Ordinance was adopted in 1983; however, the effects of this ordinance were not likely to have had a significant effect on vegetation canopy coverage until the late 1980s and early 1990s.

Between 1993 and 2002, total canopy coverage was reduced from approximately 181,077 acres to 173,907 acres which represents a net 4% loss in vegetation canopy. Based on the satellite imagery, this loss occurs in several areas throughout the County due to clearing of vegetation in the eastern and southern portions of the County for cattle grazing and other agricultural purposes along with continued residential development both west and east of I-75. Other losses may have occurred as a result of tropical storms which often result in high winds that cause uprooting of trees. Gains in canopy were also observed throughout the County, including regrowth in some of the previously cleared agricultural areas in the eastern part of the County. Although not directly quantifiable due to the scale of the satellite imagery analysis, the tree ordinance may have had a role in reducing the rate of vegetation canopy decline observed between 1993 and 2002.

The loss of vegetation canopy coverage during the 1993-2002 period resulted in gains in open land and also a large gain in water features. Gains in water coverage are likely due to two factors: 1) the construction of borrow pits and lakes to obtain fill material for new developments, highway overpasses, roadways, etc., and 2) the construction of stormwater ponds for surface water management purposes (flood reduction and water quality improvement) which was required by the water management districts as of 1984.

Vegetation Canopy Coverage by Municipality

Vegetation canopy coverages were also calculated by individual municipalities within the County. Percent vegetation canopy coverage values are presented in **Figure 3-4**. The unincorporated areas of Sarasota County comprise approximately 78% of the total area of the County and this area has the greatest percentage of vegetation canopy cover in 2002. However, the decline from 1975 has been significant (an approximately 25% loss). The City of North Port represents approximately 18% of the County's total land area and the percent of vegetation coverage is also relatively high in this municipality at just over 40%. The City of Venice and City of Sarasota represent approximately 4% of the total land area of the County, with Venice having a slightly greater percent vegetation cover (18%) than Sarasota (16%) in 2002. The Town of Longboat Key represents less than 1% of the County land area and has a vegetation canopy coverage of approximately 25%. Due to their relatively low vegetation canopy coverages and high percentages of land converted to urban development, the Cities of Sarasota and Venice should be target areas for future urban tree planting efforts. The unincorporated areas of the County and also North Port should be targeted for strategic land acquisition of existing vegetation canopy areas.

Vegetation Canopy in Public Ownership

An analysis of the amount of existing vegetation canopy coverage which is currently in public ownership or which is targeted for acquisition was performed to estimate the level of risk of further vegetation canopy loss. As of 2002, it is estimated that there were approximately 173,907 acres of vegetation canopy remaining in the County (see **Table 3-1**). The area of existing publicly owned land is shown in **Figure 3-5** and **Table 3-2**. Approximately 100,000 acres of land are currently protected through land acquisition by the County's ESLPP program or other local (SWFWMD) and state (FDEP) land acquisition programs. Another 21,169 acres are currently targeted or are in contract negotiations for purchase within the County. Based on these values, approximately 33% of the existing vegetation canopy in Sarasota County is in public ownership. Based on the combined total of targeted/pending and existing publicly owned parcels, approximately 46% of the County's vegetation canopy is anticipated to be under public ownership within the near future. This represents a significant reduction in risk of future losses of vegetation canopy cover and a valuable environmental resource to the residents of the County.

It should be noted that the historical vegetation canopy composition has changed during the past century with the suppression of natural fires. In some areas, lands managed by the County's Natural Resources division are undergoing tree thinning to reduce fire loads and to restore historic forest/prairie communities and so vegetation canopy cover may actually decrease slightly within publicly owned lands as a result of forest restoration activities.

3.0 Results and Discussion

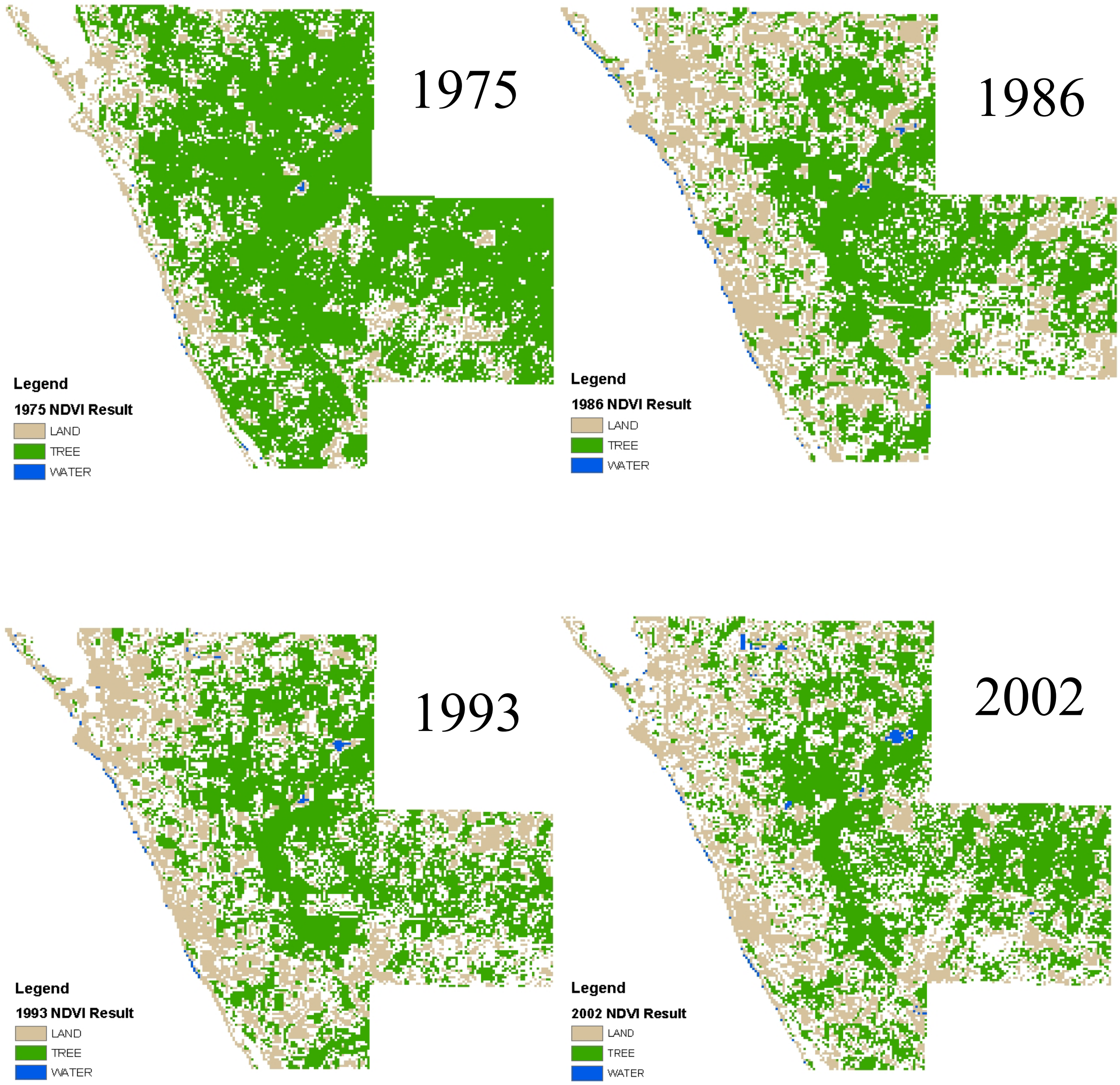
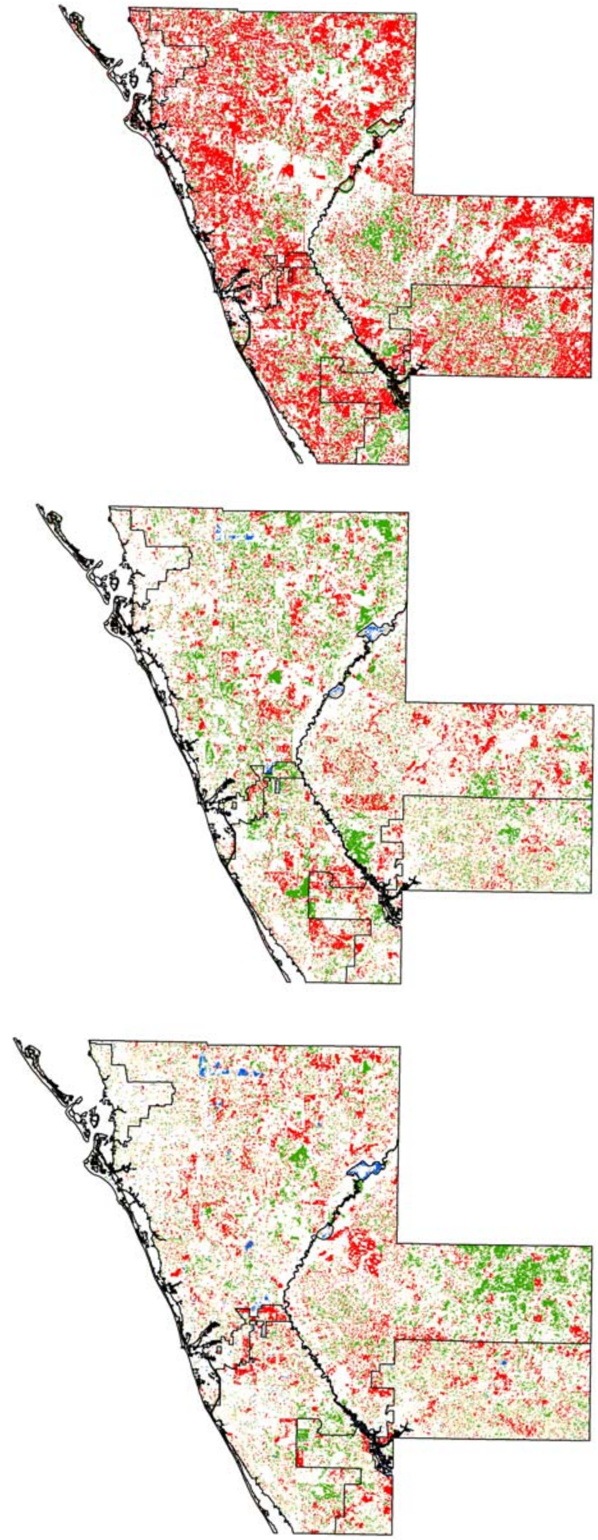


Figure 3-1. Vegetation canopy coverage in 1975, 1986, 1993, and 2002 for Sarasota County based on Landsat imagery analysis.

3.0 Results and Discussion



1975 to 1986

1986 to 1993

1993 to 2002

Figure 3-2. Change analysis in vegetation canopy coverage in Sarasota County between 1975-1986, 1986-1993, and 1993-2002 based on Landsat imagery analysis. Areas in red represent vegetation canopy loss, areas in green represent vegetation canopy gain. Areas in blue represent water features.

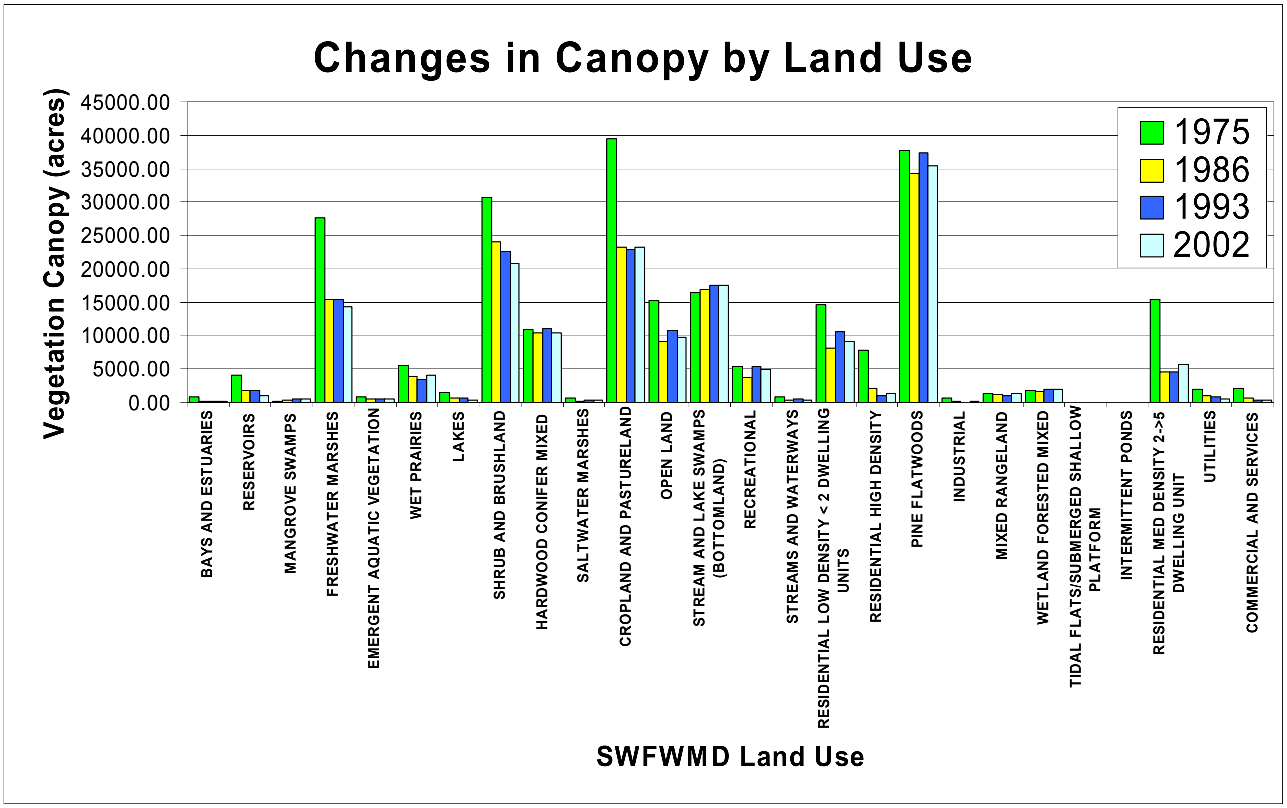


Figure 3-3. Changes in vegetation canopy cover with respect to land use (1999).

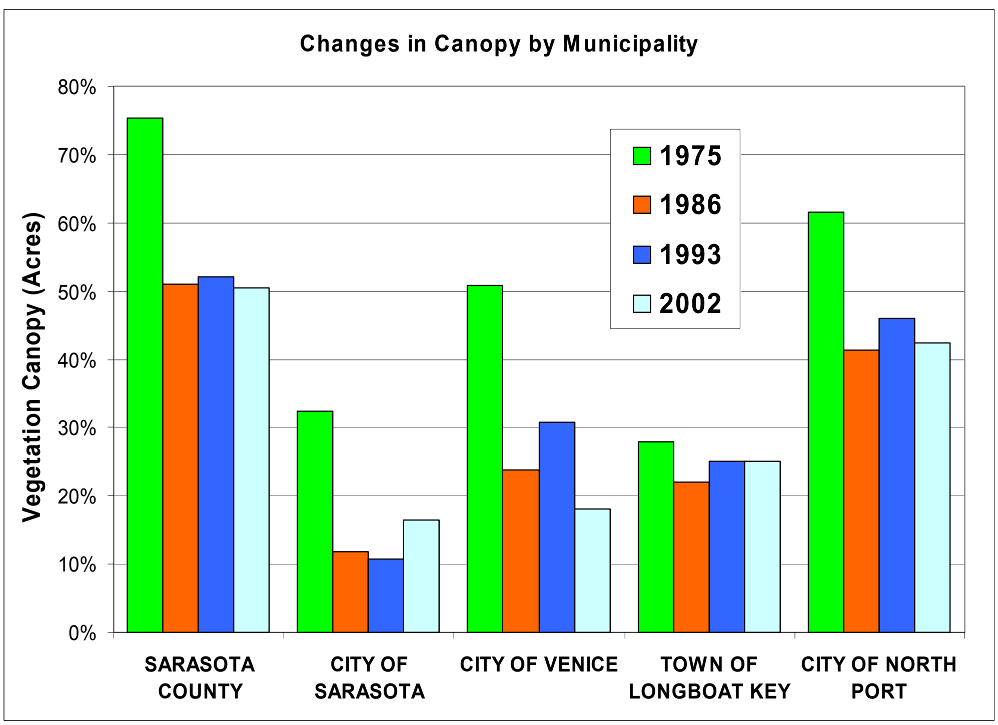


Figure 3-4. Percent vegetation canopy cover by municipality in Sarasota County.

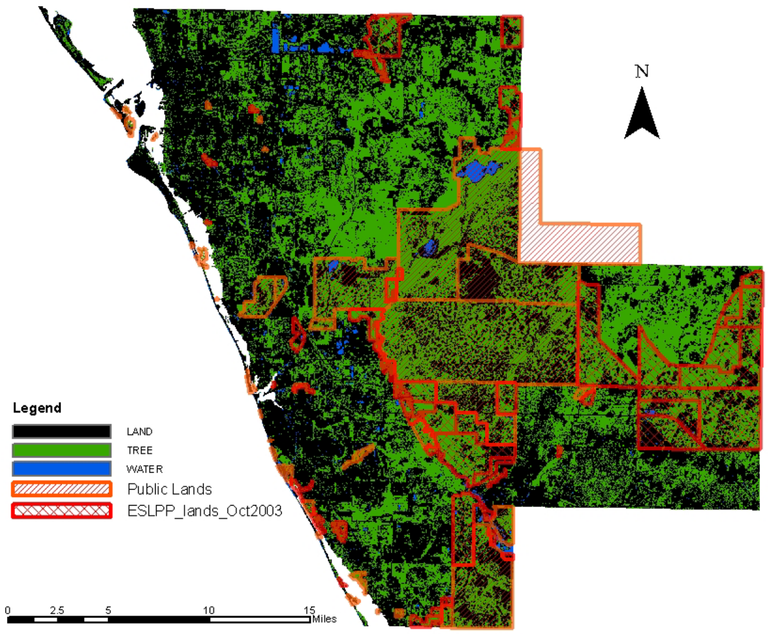


Figure 3-5. Vegetation canopy cover in public ownership in Sarasota County.

Table 3-2. Vegetation coverage within conservation land acquisition programs in Sarasota County.

Status	Total Acres	Acres of Canopy	% Canopied
ESLPP Protected	13,707	9,071	66%
ESLPP Targeted/Pending	33,958	21,169	62%
Other Public Lands	85,381	49,127	58%
Total:	133,045	79,367	60%

Urbanized versus Rural Area Comparisons

An additional spatial analysis was performed to calculate vegetation canopy coverage in the more urbanized portions of the County compared to the relatively rural or undeveloped areas. These areas were designated by splitting the County into two separate areas, lands east of I-75 and unincorporated County lands west of I-75. Unincorporated areas were those lands outside of the Cities of Sarasota, Venice, North Port, and Town of Longboat Key. This generally followed the delineation of the most recent Sarasota County Urban Service Area boundary (2003) and also the 2050 Comprehensive Plan designations for future development which mainly involves areas east of I-75.

In 1975, the area east of I-75 had a vegetation canopy coverage of approximately 80%, which declined to approximately 58% in 1986 (**Figure 3-6**). The canopy has remained relatively stable at around 58% through 2002. The urbanized unincorporated areas west of I-75 had a vegetation canopy cover of approximately 47% in 1975. This is largely due to the fact that most of the development in this coastal area was constructed prior to the 1980s (see **Figure 2-4**). Vegetation canopy coverage decreased to approximately 30% in 1986 and has been relatively stable since that time through 2002.

3.0 Results and Discussion

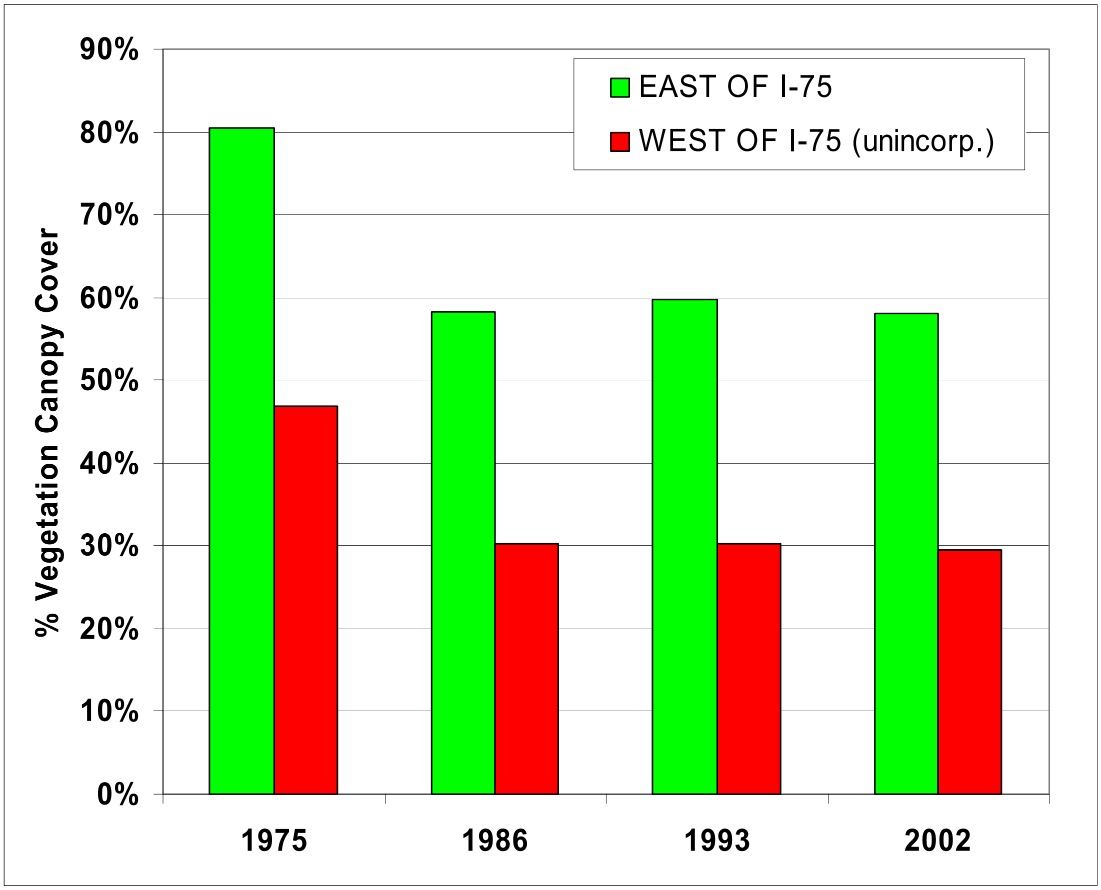


Figure 3-6. Changes in vegetation canopy cover in areas east (rural) of I-75 versus west (urbanized unincorporated areas) of I-75.

The non-profit organization American Forests has developed recommended goals for tree canopy coverage based on data developed from across the U.S. The American Forests canopy cover goals for different land uses are as follows:

- 15% for commercial areas
- 25% for urban residential areas
- 60% for suburban areas; and
- 40% average canopy cover.

The exact definitions for each of these land use types are somewhat arbitrary since these categories vary across different planning agencies and comprehensive plan designations. However, these values can be used as a relative benchmark to compare a communities' vegetation canopy cover with other areas of the country. Based on the satellite imagery analysis and the division of the County into urban versus rural areas described above, the areas east of I-75 meet the American Forests canopy goal of 60% for "suburban" areas and exceed the 40% "average" goal for canopy cover. The urbanized unincorporated areas west of I-75 do not meet the 40% average or 60% goal for "suburban" land use, but do meet the 25% canopy goal for urban residential and 15% goal for commercial, if one assumed that these were the two predominant land uses west of I-75. A discussion of the local land use analysis is discussed below which has slightly different results based on more precise vegetation canopy mapping methods.

3.0 Results and Discussion

Age of Development versus Vegetation Canopy Cover

During the local analysis, it was observed that older developments/neighborhoods within the County often had larger trees with relatively large canopy cover compared to more recent residential and commercial developments. This would be expected since trees either retained or planted during the development of urban areas before 1970 would have more than 30 years of growth compared to recent developments. An example of this can be seen in comparisons of 1940s and 1999 aerial photography (**Figure 3-7**). In the 1999 photography, the growth of canopy during the past 50 years mainly follows along individual street corridors. It was also assumed that low density residential sites may have greater canopy cover than medium or high density sites since the amount of land needed for building structures would be relatively small compared to the overall lot size.

Using the vegetation canopy cover maps generated for the local analysis, the percent cover of vegetation canopy was plotted against the age of the building structure at each of the nine residential sites and three commercial sites (**Figure 3-8**). Several of the residential sites had a mix of building ages since not all of the parcels within a study site area were developed at the same time. As predicted, most of the areas with structures constructed prior to 1980 (Sites 1, 2, and 6) had the greatest percent vegetation canopy cover. These sites are located in an older section of the City of Sarasota and included both low and medium density residential and commercial development. Only one of the three commercial sites (Site 6) met the American Forests goal of 15% for canopy cover in commercial areas. Due to the mix of building ages at many of the remaining sites (pre 1970s to 2000), no strong relationship was apparent between building age and canopy cover.

Surprisingly, a low percent canopy cover (8%) was observed at the low density residential area at the Myakka Valley Ranches (Site 8) where homes were constructed between 1970 and 1980. The lots in this subdivision were typically cleared of most tree and shrub vegetation with only a few larger trees retained in the landscape. One of the highest vegetation canopy cover values was at a high density site (Site 17) in the City of Venice. The majority of structures at Site 17 were constructed prior to 1980, which would have allowed greater vegetation canopy growth at this site. Site 12 is a condominium complex on Siesta Key which is constructed between two other condominiums leaving little room for tree plantings resulting in a very low percent canopy cover (3%). Only two of the nine residential sites (Sites 1 and 2) met the American Forests goal of 25% canopy coverage for urban residential land use; both of these sites were built out before 1980.

Local Analysis

A total of 1,674 trees representing 68 species were inventoried during the local analysis field data collection surveys within the County. Trees ranged in height from <25 ft. to >45 ft. with a mean of approximately 30 ft. Mean tree diameter at breast height (DBH) was 27.1 in. The overall health conditions of trees was measured by examining twig growth, presence of branching, and crown health. Tree health ranged from poor (score = 1) to excellent (score = 5); the average tree health was 4.9 (excellent).

The dominant tree species based on abundance for all the sites combined (those representing more than 4% of all species) were:

1. Sabal Palm (17%)
2. Slash Pine (15%)
3. Laurel Oak (10%)
4. Live Oak (9%)
5. Queen Palm (8%)
6. Washingtonia Palm (6%)
7. Australian Pine (4%)

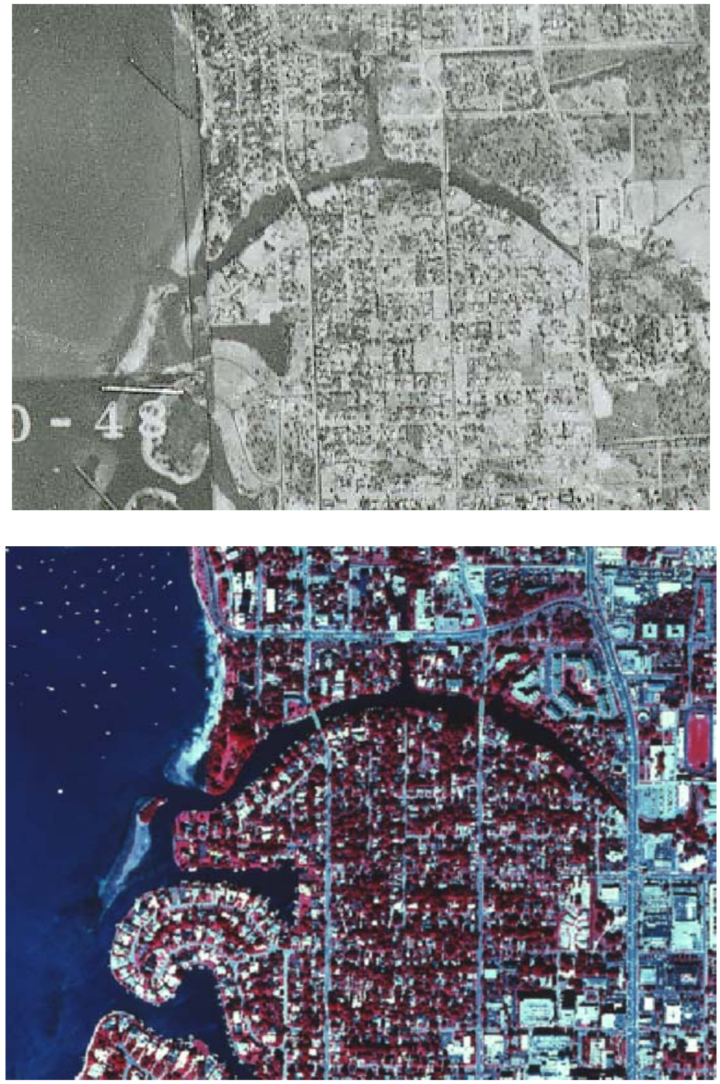


Figure 3-7. Comparison of historical (top, 1948) versus recent (bottom, 1999 infrared) aerial photography and vegetation canopy cover in a residential area near Hudson Bayou in Sarasota County.

The abundance of trees, by species, was also evaluated with respect to land use category. A plot of this data is provided in **Appendix D**. Palms (sabal, queen, Washingtonia) were the most abundant species in high density residential land uses while slash pines and sabal palms were abundant in open land areas. Live oak, Australian pine, and sabal palms were the most predominant species at recreational lands. Queen palm and live oak trees were most prevalent at medium density residential land uses. Sabal palm, slash pine, laurel and live oak trees were the most abundant species in low density residential land uses. Although three replicates of each land use type were surveyed, this still represents only a fraction of the entire County and so extrapolation of the characteristics of the various vegetation communities in each land use should be interpreted with caution. The average percentage of native species for all sites was approximately 50%. This value is similar to the 46% reported in the City of Tampa (Campbell and Landry, 1998). In addition, laurel oak which is a relatively short-lived species (~50 years) represented 10% of species found within the urban sites. In the future, these trees may represent a significant canopy loss in the urban areas as they naturally decline.

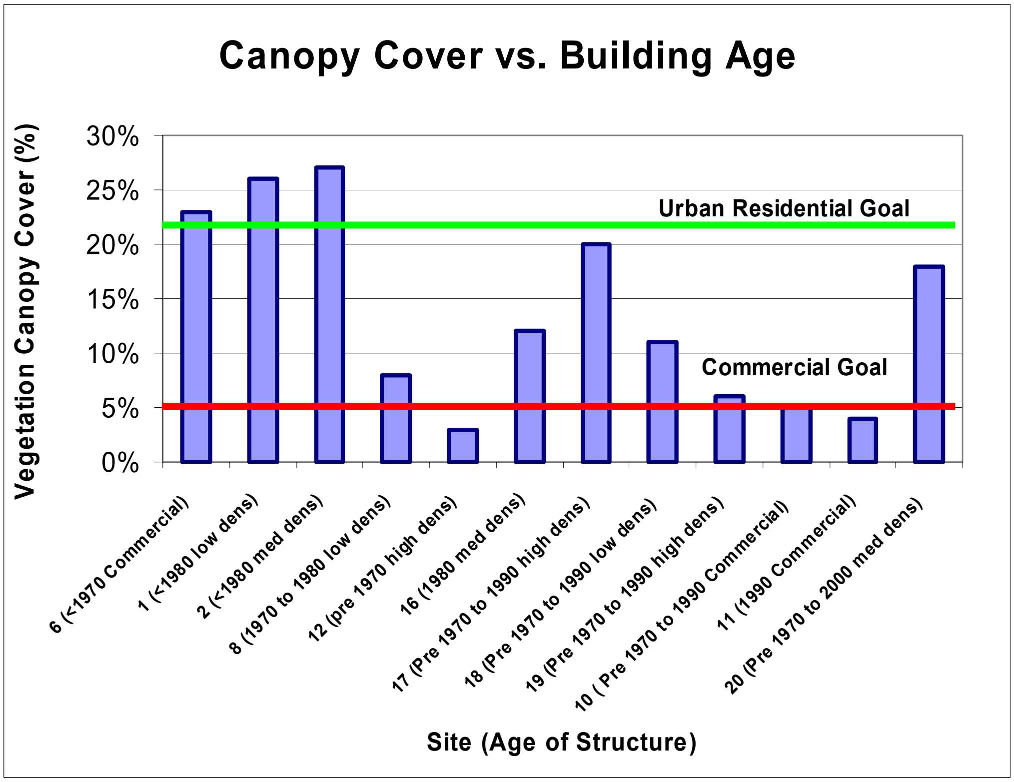


Figure 3-8. Vegetation canopy cover versus age of building structure at the residential and commercial sites evaluated in the local analysis. Age of structure and residential density type are in parentheses.

Stormwater Interception

Studies by the Center for Urban Forest Research (CUFR) at the University of California (Davis) have illustrated the benefits of trees in attenuating rainfall (Xiao et al., 1998). During a rainfall event, trees can intercept rainfall on their leaves, branches, and trunk, or the rainfall falls directly through the canopy to the ground (throughfall). The intercepted water is temporarily stored on leaf and bark surfaces where it may evaporate. Eventually a tree's storage capacity is filled and rainfall may drip from the leaf surfaces to the ground. The amount that is intercepted is calculated as the sum of canopy surface water storage plus evaporation. The duration and magnitude of the rainfall event, tree species and architecture, and weather conditions may influence the amount of rainfall intercepted by an individual tree. As the amount of precipitation increases for a given storm, the effectiveness of the tree canopy diminishes since the carrying capacity for the tree declines once all of its surfaces are saturated with rainfall.

Studies performed to measure the interception of rainfall by various tree species include those by Xiao et al. (1998), Xiao and McPherson (2002), Owens and Lyons (2002), and Jackson and Wallace (1999). Based on a review of this literature, rainfall interception ranges from about 5% to nearly 100% with an average of approximately 11%. The variability in interception is mainly due to differences in the intensity (amount and duration) of precipitation, humidity, temperature, and tree species (leaf area, branch structure, canopy cover). The percent of rainfall intercepted is generally greatest for small short duration storms and with trees having large leaf areas. Xiao et al. (1998) found that broadleaf evergreens, conifers, and broadleaf deciduous, had the greatest leaf areas, respectively. Species that are broadleaf evergreens are likely to be more effective since they retain leaf out conditions most of the year and can therefore intercept a greater proportion of rainfall than seasonally deciduous species. Owens and Lyons (2002) found that approximately 35% of rainfall is intercepted during a 1 inch storm event using a juniper tree model in Texas.

The study by Xiao and McPherson (2002) estimated that annual rainfall interception by 29,299 street and park trees was 193,168 m^3 (6.6 m^3/tree), or 1.6% of total precipitation. They also found that the annual value of avoided stormwater treatment and flood control costs associated with reduced runoff was $110,890 ($3.60/tree). Interception rates varied by tree species and sizes and rainfall interception ranged from 15.3% (0.8 m^3/tree) for a small *Jacaranda mimosifolia* (3.5 cm diameter at breast height) to 66.5% (20.8 m^3/tree) for a mature *Tristania conferta* (38.1 cm). In a 25-year storm, interception by all street and park trees was only 12,139.5 m^3 (0.4%) with each tree yielding $0.60 (0.4 m^3/tree) in avoided flood control costs. They found that rainfall interception varied seasonally, averaging 14.8% during a 21.7 mm winter storm and 79.5% during a 20.3 mm summer storm for a large, deciduous *Platanus acerifolia* tree.

In the study by Xiao et al. (1998) in Sacramento, California, approximately 11% of the annual rainfall was estimated to be intercepted by trees. It was also determined that, generally, large trees with small leaves are most efficient at rainfall interception. The seasonal patterns of rainfall are also important relative to leaf-on conditions, for example, greater rainfall is intercepted if evergreens are the predominant species in areas where rainfall is greatest during the winter. This effect is probably less important in Florida, where the peak of the rainy season is in the summer, a time when most tree species have full canopies. In addition, due to Sarasota's subtropical climate, many species are evergreen or only semi-deciduous with relatively brief periods of defoliation. Although data regarding interception rates do not specifically exist for tree species native to Florida, the study by Xiao and McPherson (2002) in southern California demonstrated much higher average rates of interception occur in Santa Monica (27%) than in the Central Valley cities of Modesto and Sacramento (11%). While this difference may be explained by differences in meteorology, it is likely that species composition is playing a role with more broadleaf evergreen species present in the more subtropical climate of Santa Monica. Therefore, it is expected the benefits of rainfall interception in Sarasota would be greater than what could be expected from temperate climates and most likely greater than dry subtropical climates such as southern California.

To further evaluate this hypothesis, Sarasota County stormwater staff (Steve Suau) recommended an analysis of historical rainfall distributions to identify the distribution of typical storm events in southwest Florida using similar methods as Harper et al. (2003). Using a representative rainfall station located at Oscar Scherer State Park, daily rainfall data were obtained from the SWFWMD for the available period of record which included the years 1975 through 1997. A probability distribution was performed on all daily rainfall events based on 0.10 inch increments (e.g., 0.00-0.10 inches, 0.11-0.20 inches, etc.). Based on this analysis, it was determined that approximately 86% of all storm events that have been measured between 1975 and 1997 were equal to or less than one inch (**Figure 3-9**). Based on this analysis, the estimated reduction in direct rainfall would be expected to be similar to those reported for Santa Monica and Texas, approximately 27 – 35%.

It should be noted that the capacity for the tree canopy to capture and attenuate rainfall diminishes as the duration and intensity of a storm event increases. In other words, the tree canopy should not be expected to serve as a flood control management tool. Xiao et al. (1998) evaluated a series of flooding events and found that canopy interception was greatest for smaller, shorter storms (2-year storm event) than for larger and longer storm events (200-year storm event). Once the storage capacity of a tree canopy is filled, the remainder of the rainfall event passes through as groundfall and can result in runoff.

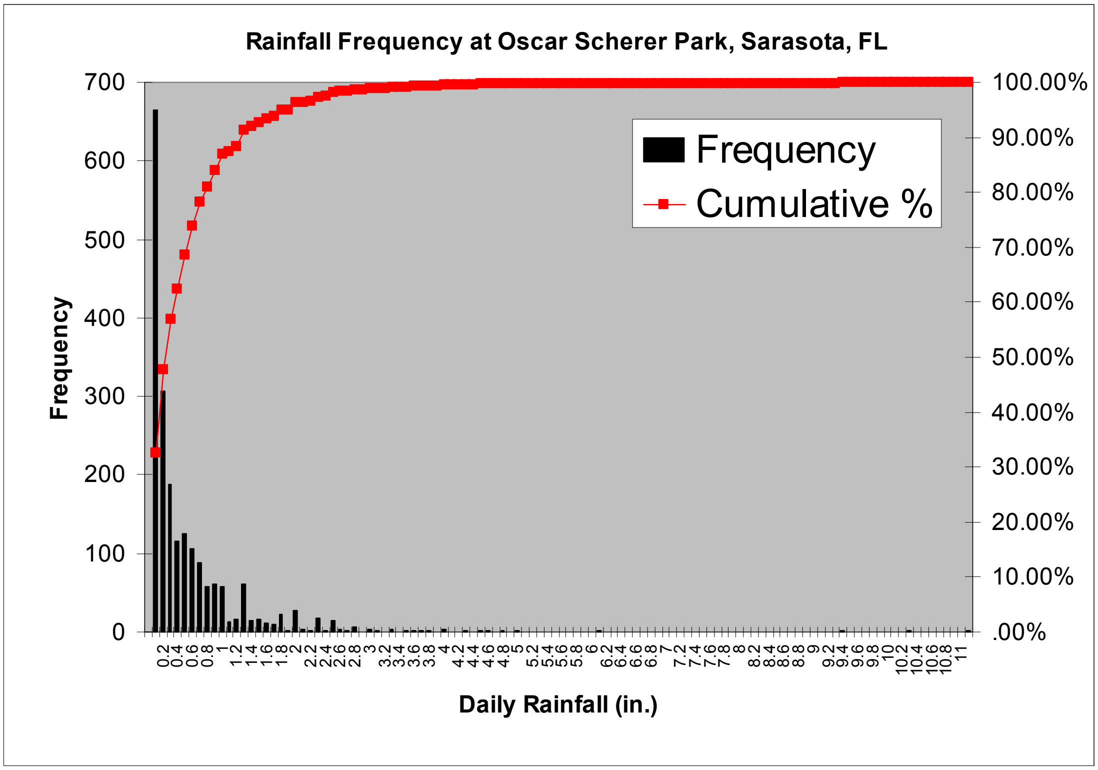


Figure 3-9. Daily rainfall distributions at Oscar Scherer Park gage between 1975 and 1997. (Data source: SWFWMD)

The benefit of rainfall interception is probably best realized in reductions of non-point source pollution. Pollutant loads that are washed off of impervious surfaces are typically estimated by multiplying the volume of runoff times an average pollutant concentration (i.e., event mean concentration) found in runoff for a given land use. By reducing the amount of rainfall that falls on a given area of impervious surface, a direct reduction in pollutant loads may be achieved through the strategic planting of trees over impervious areas. As a result, trees are more likely to enhance water quality by intercepting large numbers of small rain events than providing flood control. Flooding usually occurs during or immediately after extreme storm events which generate rainfall amounts well beyond the point where canopy storage has been exceeded.

In summary, one of the most important factors for preserving or enhancing vegetation and forest canopy cover may be the effectiveness of the canopy in reducing pollutant loads from stormwater runoff. In addition, unlike other types of stormwater BMP's, trees/vegetation become more valuable in reducing non-point source pollution with age, since the rainfall interception benefit is directly related to leaf surface area.

Air Pollution Removal Modeling

The results of the air pollution modeling are presented in **Appendix D** and are summarized in **Table 3-3**. The average air pollution removal savings were greatest for open land sites, followed by low density residential, and recreational lands. The CITYgreen model uses an average pollutant removal rate based on previous modeling conducted for several cities in the U.S. (Atlanta, Austin, Baltimore, Boston, Denver, Milwaukee, New York, Philadelphia, St. Louis, and Seattle). Air quality in Sarasota County is typically of a much higher quality than these highly urbanized/industrialized cities and so the model results are likely to overestimate vegetation benefits for southwest Florida. Generally, air pollutant removal increased with increasing acreage of vegetation canopy and the number of trees present at a given site (**Figure 3-10**). Sites 3 and 15 had the greatest air pollution removal savings of $751 and $1,140, respectively. These sites also had the greatest removal on a per acre basis since the majority of both sites were covered by vegetation canopy. Sites with the least air pollution savings were those with little to no vegetation canopy and the fewest trees including Sites 7 (recreational), 11 (commercial), and 14 (open land). Based on these relationships, it can be predicted that tree planting efforts should help to improve air quality.

Table 3-3. Average air pollution cost savings by land use type based on the 18 local analysis sites.

Land Use Type	Avg. Air Pollution Removal Savings
Commercial	$ 97.00
Open Land	$ 638.67
Recreational	$ 219.67
Residential High Density	$ 114.00
Residential Low Density	$ 293.67
Residential Med Density	$ 206.67

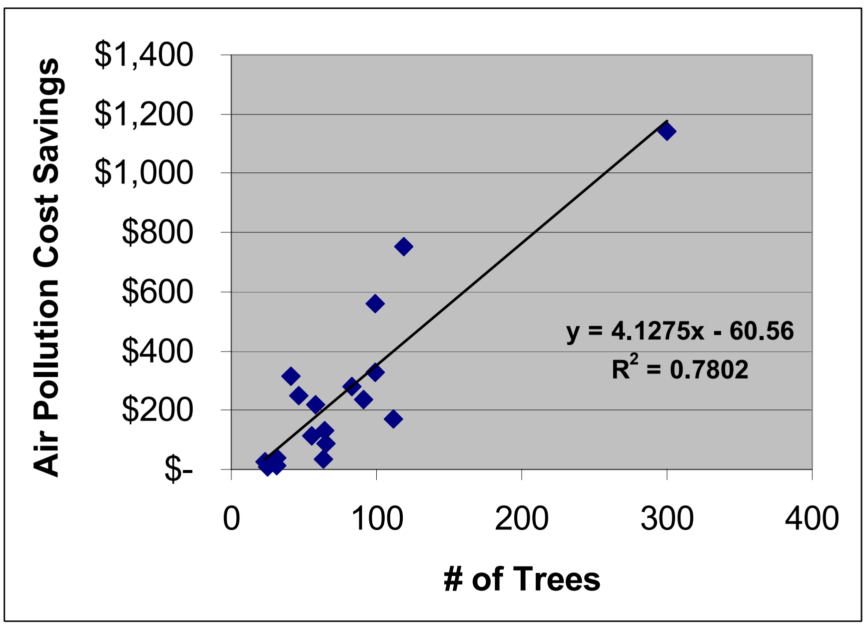


Figure 3-10. Plot of air pollution control cost savings versus number of trees at each of the 18 local analysis sites.

Carbon Storage and Sequestration Modeling

CITYgreen quantifies the role of urban forests in removing atmospheric carbon dioxide and storing the carbon in tree biomass. Using the tree diameter data collected in the field, CITYgreen estimates the age distribution of trees within a given site and assigns one of three age distribution types. Type I represents a distribution of young trees, Type 2 represents a distribution of mature trees, and Type 3 describes a site with a balanced distribution of ages. Sites with mature trees (with more biomass) are assumed to remove more carbon than those with younger trees (less biomass). Each distribution type is assigned a multiplier, which is combined with the overall size of the site and the site's canopy coverage to estimate the amount of carbon removed from a given site. CITYgreen estimates both the annual rate at which carbon is removed and the amount of carbon storage in existing trees (in tons).

The majority of sites in Sarasota County had Type 2 age distributions of trees (mature). Site 10 (commercial) had relatively young trees since the site was developed in the 1990s. Site 15 had an average or Type 3 distribution of trees with both young saplings and older tree species represented at the site. The greatest average carbon storage was found at open lands sites due to the larger site sizes and numbers of trees typically present (**Figure 3-11**). The lowest carbon storage was found at commercial and high density residential sites which typically had smaller and fewer trees. Except for commercial sites, where trees were typically younger in age (thereby having a greater potential for future carbon uptake rates), carbon sequestration rates followed the same pattern with the greatest rates at larger, heavily treed sites and least at smaller sites with fewer but more mature trees.

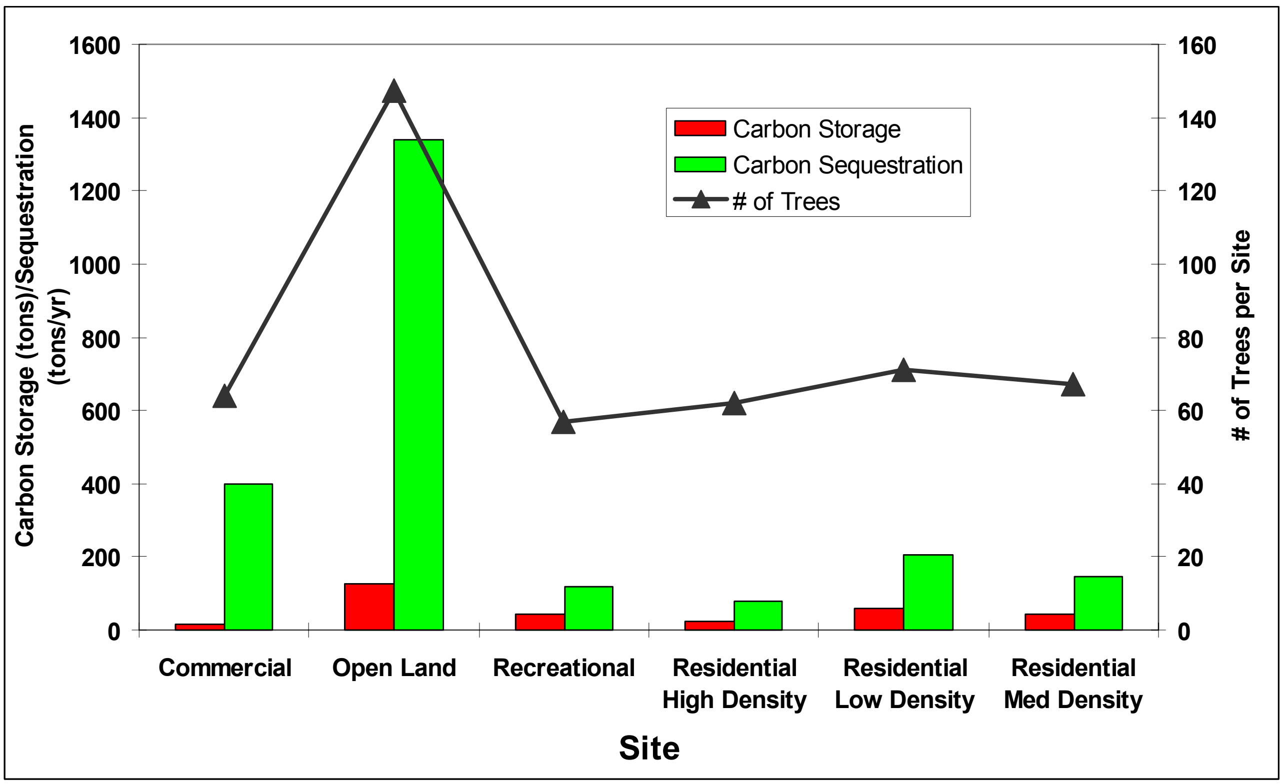


Figure 3-11. Plot of carbon storage and sequestration rate values at each of the 18 local analysis sites.

Energy Conservation Modeling

The energy conservation model included in the CITYgreen application estimates the kilowatt-hour saved based on the location and height of a tree with respect to an existing residence. Only the residential land use sites were modeled to determine energy conservation savings. The energy conservation analysis utilizes methods developed by Jill Mahon of AMERICAN FORESTS, interpolated from research by Dr. Greg McPherson of the USDA Forest Service. CITYgreen estimates the energy conservation benefits of trees resulting from direct shading of one- and two-story residential buildings. Trees are most effective when located such that air conditioners, windows, or walls are shaded, and when located on the side of the home receiving the most solar exposure. This is typically the west side of the home, followed by the east and south. CITYgreen assigns each tree an energy rating, 1 through 5, based on location characteristics and information about tree size and shape. For this analysis, a large tree located near the west side of a building and shading an air conditioner or window would be assigned a near-maximum energy rating. The results of the CITYgreen model should be considered carefully as there are a number of limitations. For example, the model does not account for recent research in Florida which determined that direct shading of air conditioning units did not provide a significant energy savings (Parker, et al., 1996). However, the results of this study are consistent with other studies and can be used for comparative purposes to other communities (Simpson and McPherson, 1998).

Average energy cost savings by residential land use type are presented in **Table 3-4**. Despite having similar tree densities (# of trees per acre) among the different residential land use sites, the average energy costs savings per home varied from $9.90 for medium density sites to $33.46 for low density sites. The higher energy cost savings at low density sites may be due to the fact that larger trees were typically found along the west wall of most of the homes in this land use category (see **Appendix B**). Medium density home sites evaluated during this study tended to be oriented in a north-south direction and were too close together to allow plantings of large trees between the homes along the westernmost walls. The high density residential sites were a mix of multi-story condominiums (which had little to no shading effect from adjacent trees above the first story) and single story mobile homes. The mobile homes were also spaced too close together to allow for the growth of large canopied tree species.

Table 3-4. Average energy cost savings by residential land use type based on the 18 local analysis sites.

Type	Total Energy Cost Savings	Trees/Acre
Residential High Density	$ 13.27	11.5
Residential Low Density	$ 33.46	11.3
Residential Med Density	$ 9.90	12.9

Combined Cost Saving Calculations

Based on the combined economic benefits calculated in the previous CITYgreen analyses, an estimate of the total annual economic value of the vegetation canopy within urban areas of Sarasota County has been calculated and provided in **Table 3-5**. This table is based on extrapolation of the average cost savings for each of the six urban land use types evaluated multiplied by the number of acres of each land use type which currently exists in Sarasota County. Based on these calculations, open land provides a significant economic benefit to the County in terms of air pollution removal. The existing economic benefits provided by this land use type are significant, because nearly 26,000 acres of this land use type remains in the County. However, it should be noted that the values used to generate the cost savings values for this land use were based on only three sites, including two sites in the North Port area which are heavily canopied. These sites were originally platted and cleared for development in the 1970s (hence their designation as “open land”) but were never built out. In concert with existing land development codes and tree protection ordinances, implementation of more innovative designs to protect the existing vegetation canopies in these areas should be considered since the greatest economic benefits for air and water quality protection are represented by this land use type.

The existing vegetation canopy in medium density residential land use also provides a significant economic benefit to Sarasota County. Many older neighborhoods are becoming more heavily canopied as a result of decades of tree growth since their original development. Tree planting programs at recreational and commercial lands may also have a significant effect on improving air and water quality, since these areas currently have relatively low canopy cover compared to other land use types. However, these effects will likely take several years to be realized.

Table 3-5. Estimated annual economic value of Sarasota County's vegetation canopy based on cost savings for air pollution and residential cooling.

Land Use Type	Acres in County	Value of Tree Canopy
Residential Medium Density	29,512	$ 2,196,381
Residential Low Density	21,664	$ 1,153,655
Residential High Density	16,462	$ 750,452
Recreational	8,004	$ 273,557
Open Land	25,902	$ 3,206,156
Commercial	6,104	$ 143,563
Total:	**107,647**	**$ 7,723,764**

*value based on total annual savings for air pollution removal and residential cooling effects.

Comparisons to Other Similar Studies

Several communities throughout the U.S. have performed similar studies to evaluate temporal trends and economic benefits of the urban forest canopy (Campbell and Landry, 1998; American Forests, 2001, 2002). The results of Sarasota County's vegetation canopy analysis were compared with these other recent studies to understand the relative health of County's urban forest with respect to other communities and also American Forests canopy goals. **Figure 3-12** includes the individual vegetation canopy cover values by municipality derived from the satellite imagery analysis for Sarasota County as well as those for the City of Tampa, Atlanta, Portland, and New Orleans urban forests. The unincorporated area of Sarasota County ("Sarasota County" in **Figure 3-12**) and City of North Port areas had greater vegetation canopy cover percentages than any of the other study sites selected for comparison. The Cities of Sarasota and Venice had lower vegetation canopy coverages than the City of Tampa (based on 1996 imagery) and exceeded the commercial guidelines for vegetation canopy cover, but fell below the urban residential guideline. The metro Atlanta, Portland, and New Orleans areas had greater canopy coverage areas than the City of Sarasota and Venice, and the Town of Longboat Key exceeded both the urban residential and commercial guidelines.

It should be noted that although the techniques for vegetation canopy cover calculations were nearly identical among this and other previous studies, the land use types, vegetation species, and study area sizes were highly variable. The metro Atlanta study area covered an area of 775,000 acres (nearly twice the size of Sarasota County) and included both the downtown area as well as suburban residential areas. The Portland study area covered nearly 7 million acres and included several state and national forest areas, as well as the Portland metropolitan area. The New Orleans study area was only 124,160 acres in size and focused mainly on the highly developed downtown area of the city. Despite the large degree of variability among the different study site conditions, the current County-wide vegetation canopy coverage of 47% exceeds a number of metropolitan areas throughout the continental U.S. However, the most urbanized areas of the County (Cities of Sarasota and Venice) have relatively low vegetation canopy coverage compared to highly developed areas like Atlanta and New Orleans and should be targeted for future tree planting efforts.

3.0 Results and Discussion

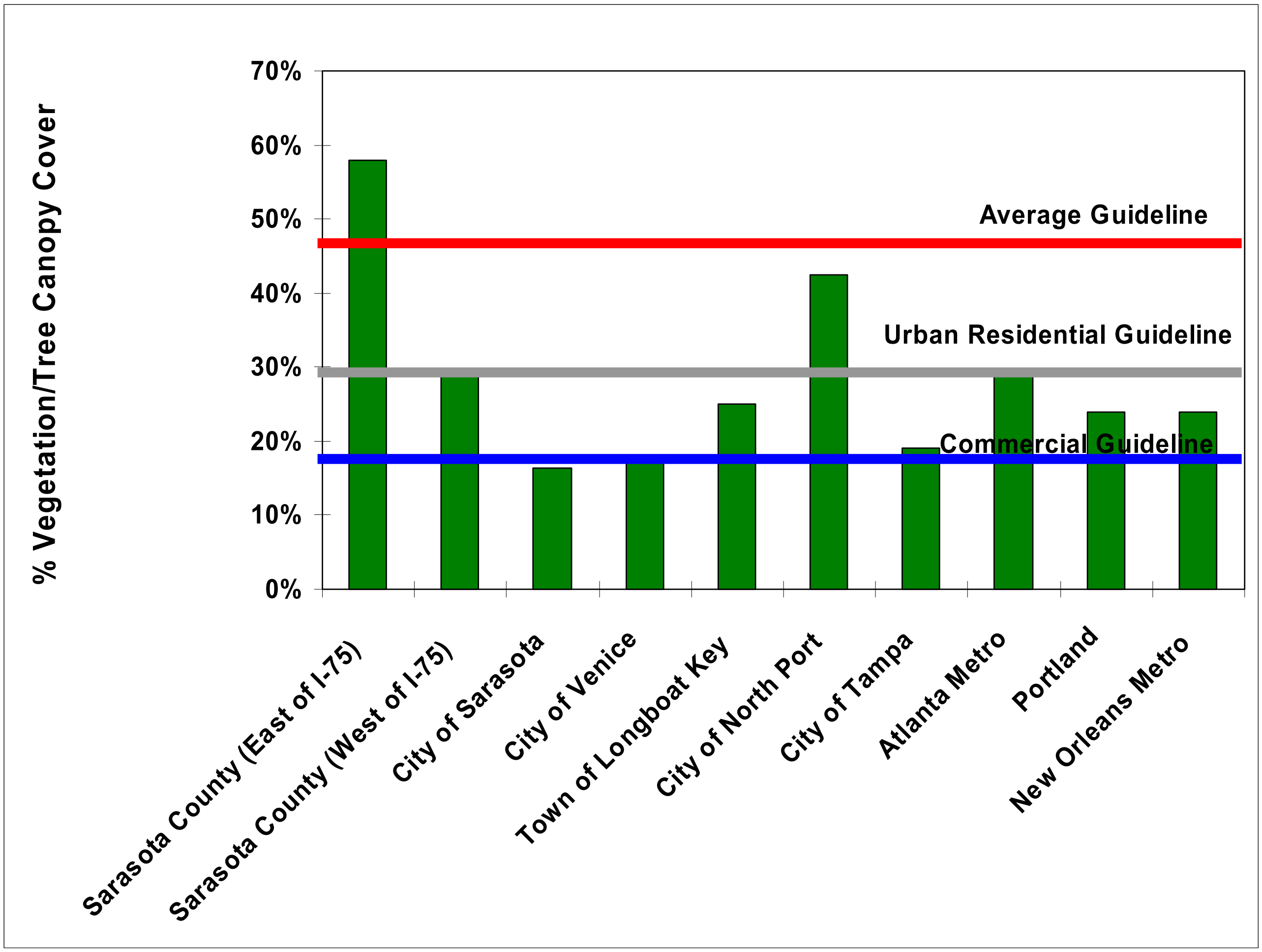


Figure 3-12. Vegetation/tree canopy cover estimates from Sarasota County and several study areas throughout the continental U.S. Guideline values are based on American Forests recommended canopy cover goals.

Recommendations

This study has demonstrated trees and other vegetation are a valuable component of Sarasota County's infrastructure. The results of this study also show that vegetation canopy coverage in the urbanized areas of Sarasota County has declined by approximately 33% since the 1970s and commercial and urban residential canopy cover in some areas of the County are below national goals developed by the non-profit group American Forests. The remaining vegetation canopy provides a significant economic and environmental benefit to the residents and visitors of the County and should be protected to the best extent practicable under the current policies set forth by the County's comprehensive plan. Several recommendations can be made based on the analysis of the vegetation canopy coverage and local site analysis performed in this study:

1. ***Evaluation of Sarasota County Tree Protection Policies*** - The vegetation and tree canopy coverages calculated from this study should be used to evaluate key public policies such as the County's Comprehensive Plan and future tree protection ordinances. As demonstrated in this study and many others across the U.S., the principle ecological and economic benefits are directly related to the percentage of canopy cover and not necessarily numbers of individual trees. Canopy cover goals

should be set by land use type within the comprehensive plan and local development ordinances. Sarasota County implemented its tree protection policy in 1983 through ordinance no. 83-44. This ordinance was amended in 1995, 1998, and 2002. The October 2002 amendment was the adoption of a program for the designation and preservation of grand trees. Grand trees were determined to be an important component of the urban forest, and have unique and intrinsic values to the general public due to their size, age, and ecological value. The apparent effects of the County's tree protection program are the stabilization of vegetation canopy coverage during the past two decades. However, future re-evaluations of vegetation canopy cover every three to five years should be performed using the same methodology presented in this report to monitor the effects of existing tree protection programs, especially in areas east of I-75 where the greatest development pressures are likely to occur.

2. ***Conduct Additional Research in Southwest Florida to Determine Rainfall Interception by Native Vegetation Species*** – Several studies evaluating tree canopy cover and rainfall interception have been completed recently, however, none were found that specifically addressed vegetation species or meteorological conditions unique to southwest Florida. Additional research in this area would be extremely useful in assessing economic benefits of the vegetation/tree canopy cover for reducing/attenuating stormwater runoff in Sarasota County and other areas in the region.

3. ***Implementation of Strategic Tree Planting Programs for Stormwater and Air Quality Improvement*** - Based on the results of previous studies evaluating the mechanism for rainfall interception by tree canopy, future tree plantings in urban areas should target residential areas, open lands and areas adjacent to impervious surface areas (e.g., roads and parking lots). Rainfall interception by the tree canopy will have the greatest effect when impervious surfaces are directly shaded/covered by the canopy since nearly all of the rainfall falling on impervious areas runs off into drainage systems. Sarasota County Public Works has already begun implementing a street tree planting program where tree plantings are incorporated into the medians and shoulders of new roadway improvement projects. An example of an optimal tree canopy configuration for reducing stormwater runoff is shown in **Figure 3-13**. This is a typical street in an older section of the City of Sarasota where the oak canopy covers a portion of the impervious road bed. The County's Public Works division has already begun implementing a street tree planting program where tree plantings are incorporated into the medians and shoulders of new roadway improvement projects. Selection of tree species which provide a large vegetation canopy, high leaf to area ratios, are leafed out year round or only briefly deciduous, and which can withstand pruning and disturbance should provide the greatest benefit to reducing stormwater runoff and pollutant loads to receiving waters. A thorough analysis to identify optimal tree planting scenarios with respect to this ongoing County program should be performed – the expected benefits could be calculated using the results of the additional rainfall interception research as proposed above.

   Additional vegetation planting efforts should target existing residential areas, possibly by providing subsidized trees to individual property owners. Since private homeowners will be responsible for maintaining subsidized trees, the cost and risk to grow out individual trees to maturity is relatively small while the economic and environmental benefits can be significant given the large area of the County which is occupied by residential development.

Figure 3-13. Tree canopy cover at a residential street in the City of Sarasota near Tuttle Avenue.

4. ***Create a High Resolution GIS layer of Sarasota County's Vegetation Canopy* –** Using existing technology and aerial photography of 1 meter resolution or better, a detailed GIS layer of the vegetation canopy should be created. This layer could be used for a variety of planning applications including development of strategic vegetation planting plans (e.g, targeting areas of greatest stormwater/water quality benefits) and evaluation of the effectiveness of the current tree protection ordinance.

5. ***Create Incentives for Homeowners to Plant Preferred Vegetation Species*** – Many communities offer a tree rebate program as incentive for homeowners to plant approved tree species in residential landscapes. Based on the results of this study, it appears that such a program would greatly benefit the urban environment in Sarasota County.

6. ***Communicate the Results of this Study*** – The results of this study should be shared with the general public and especially residential and commercial developers and agencies which regulate development. Communication could occur through brochures, information posted on the County's website, or public meetings. Brochures could be distributed to homeowners that highlight the results of this study and describe optimal planting schemes, vegetation species, and any incentive programs that developed to increase residential plantings. Through increased dialogue and feedback from the public, it may be possible to develop innovative designs or techniques that minimize vegetation canopy loss while still maintaining affordable and sustainable developments.

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APPENDIX A

CITYgreen Modeling References

References

Air Pollution Removal

Summary

The Air Pollution Removal program is based on research conducted by David Nowak, Ph.D., of the USDA Forest Service. Dr. Nowak developed a methodology to assess the air pollution removal capacity of urban forests with respect to pollutants such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), carbon monoxide (CO), and particulate matter less than 10 microns (PM10). Pollution removal is reported on an annual basis in pounds and U.S. dollars.

Dr. Nowak estimated removal rates for 10 cities: Atlanta, Georgia; Austin, Texas; Baltimore, Maryland; Boston, Massachusetts; Denver, Colorado; Milwaukee, Wisconsin; New York, New York; Philadelphia, Pennsylvania; St. Louis, Missouri; and Seattle, Washington. CITYgreen can determine which of those cities is nearest the site, or the user can manually identify the city nearest to the area being analyzed and use its results.. Or, the user can average results from all 10 cities.

The program estimates the amount of pollution being deposited within a certain given study site based on pollution data from the nearest city then estimates the removal rate based on the area of tree and/or forest canopy coverage on the site.

Technical Methodology

The methodology determines a pollutant removal rate, or flux (F), by multiplying the deposition velocity (V_d) by the pollution concentration (C).

$$F\ (g/cm^2/sec) = V_d(cm/sec) \times C\ (g/cm^3)$$

The pollutant flux is then multiplied by the size of the area during periods in which the pollutant is known to exist there. This makes it possible to estimate the total pollutant flux for that surface by the hour. Hourly fluxes can be summed to estimate daily, monthly, or yearly fluxes.

Air pollution estimates generated from CITYgreen currently are designed for urban and suburban forests. Therefore, CITYgreen analyses run on rural sites that are far removed from cities may overestimate tree benefits.

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Notes: Austin SO_2 and NO_2 data were taken from Houston and may not represent actual conditions in Austin. Austin was missing O_3 concentration data for January, February, and December. Concentration data for these months were estimated based on average national O_3 concentration trend data.

Carbon Storage and Sequestration

Summary

CITYgreen's carbon module quantifies the role of urban forests in removing atmospheric carbon dioxide and storing the carbon. Based on tree attribute data on trunk diameter, CITYgreen estimates the age distribution of trees within a given site and assigns one of three Age Distribution Types. Type I represents a distribution of comparatively young trees. Type 2 represents a distribution of older trees. Type 3 describes a site with a balanced distribution of ages. Sites with older trees (with more biomass) are assumed to remove more carbon than those with younger trees (less biomass) and other species. For forest patches, CITYgreen relies on attribute data on the dominant diameter class to calculate carbon benefits.

Each distribution type is associated with a multiplier, which is combined with the overall size of the site and the site's canopy coverage to estimate how much carbon is removed from a given site. The program estimates annual sequestration, or the rate at which carbon is removed, and the current storage in existing trees. Both are reported in tons. Economic benefits can also be associated with carbon sequestration rates using whatever valuation method the user feels appropriate. Some studies have used the cost of preventing the emission of a unit of carbon—through emission control systems or "scrubbers," for instance—as the value associated with trees' carbon removal services.

Technical Methodology

Estimating urban carbon storage and sequestration requires the study area (in acres), the percentage of crown cover, and the tree diameter distribution. Multipliers are assigned to three predominant street tree diameter distribution types:

Distribution Types	Carbon Storage Multipliers
Type 1 (Young population)	0.3226
Type 2 (Moderate age population, 10-20 years old)	0.4423
Type 3 (Even distribution of all classes)	0.5393
Average (Average distribution)	0.4303

Distribution Types	Carbon Sequestration Multipliers
Type 1 (Young population)	0.00727
Type 2 (Moderate age population, 10-20 years old)	0.00077
Type 3 (Even distribution of all classes)	0.00153
Average (Average distribution)	0.00335

CITYgreen uses these multipliers to estimate carbon storage capacity and carbon sequestration rates. For example, to estimate carbon storage in a study area:

Study area (acres) x Percent tree cover x Carbon Storage Multiplier = Carbon Storage Capacity

To estimate carbon sequestration:

Study area (acres) x Percent tree cover x Carbon Sequestration Multiplier = Carbon Sequestration Annual Rate

In recent studies conducted by Dr. David Nowak and Dr. Greg McPherson of the USDA Forest Service, it has been suggested that if urban trees are properly maintained over their lifespan, the carbon costs outweigh the benefits. Tree maintenance equipment such as chain saws, chippers, and backhoes emit carbon into the atmosphere. Carbon released from maintenance equipment and from decaying or dying trees could conceivably cause a carbon benefit deficit if it exceeds in volume the amount sequestered by trees.

To maximize the carbon storage/sequestration benefits of urban trees, the USFS suggests planting larger and longer-lived species in urban areas so that more carbon can be stored, mortality rates can be decreased, and maintenance methods can be revised over time as technology improves. For more information on how to estimate urban carbon storage and sequestration, please contact the USDA Forest Service (Northeastern Forest Experiment Station, Syracuse, New York).

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Stormwater Runoff Reduction

Summary

The CITY green stormwater runoff analysis estimates the amount of stormwater that runs off a land area during a major storm, as well as the time of concentration and peak flow. The program determines runoff volume based on the percentage of tree canopy, and other landcover features as digitized by the user in the CITYgreen view or as reported in a raster data set.

The analysis also considers a variety of localized information identified automatically by CITYgreen or entered by the user, such as local rainfall patterns, soil type, and other site characteristics.

The Stormwater Runoff program incorporates procedures and formulas developed by the USDA Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), to estimate runoff volume as well as percent changes in time of concentration and peak flow. The Urban Hydrology for Small Watersheds model, commonly referred to as Technical Release 55 or TR-55, was incorporated into CITYgreen. The program uses NRCS curve numbers that represent the relative amount of imperviousness and water infiltration properties of soil and land cover. Curve numbers range from 30-98; the smaller the number the less the runoff.

TR-55 was customized with the help of Don Woodward, PE, a hydraulic engineer with NRCS, to determine the benefits of trees and other urban vegetation with respect to stormwater management.

Technical Methodology

CITYgreen's stormwater runoff analysis enables a user to map urban land cover features (grassland/shrub, trees, buildings, and impervious surfaces) and determine percentages of each landcover feature.

Landcover percentages are then combined with average precipitation data, rainfall distribution information, percent slope, and hydrologic soil group, to estimate how trees affect runoff volume, time of concentration, and peak flow. In addition, the program estimates, in cubic feet, the additional volume of water that would have to be managed if trees were removed. This volume estimate can be associated with an economic value since planners generally know the cost per cubic foot to build a retention pond in their municipality. CITYgreen also enables the user to model different landcover and precipitation scenarios to determine acceptable development or conservation practices.

The TR-55 model was designed to analyze runoff patterns during a 24-hour single storm event. Engineers and non-engineers typically design stormwater management facilities for average storm events, usually 24 hours in duration, according to NRCS. CITYgreen allows the user to input values for the amount of rain that would fall during a typical 24-hour event observed within a 2-year span. This value is based on NRCS estimates of rainfall distributions for different regions of the country.

Slope information is taken from georeferenced data. Alternatively,the user can input a slope, which can be best thought of as the estimated average slope of the site. The following formulas are used to estimate curve numbers, stormwater runoff, time of concentration, and peak flows.

Formulas Used in Calculations

Curve Numbers:
CN (weighted) = Total Product of (CN x Percent landcover area)/Total Percent Area or 100

Potential Maximum Retention after Runoff begins:
$S = ((1000/CN) - 10)$

Runoff Equation:
$Q = [\ P - 0.2\ ((1000/CN) - 10)\ ]^2/P + 0.8\ ((1000/CN) - 10)$

Flow Length:
$F = (\text{total study area acres}^{0.6}) * 209.0$

Lag Time:
$L = ((F^{0.8}) * ((S + 1.0)^{0.7}) / (1900 * ((\text{slope})^{0.5})))$

Time of Concentration:
$Tc = 1.67 * L$

Unit Peak Discharge:
$\log(qu) = C_0 + C_1 \log(Tc) + C_2[\log(Tc)]^2$

Peak Flow:
$Peak = (qu * Am * Q * Fp)$

Storage Volume:
$Vs = Vr * (C_0 + (C_1(qo/qi)) + (C_2\ ((qo/qi)\ (qo/qi))) + (C_3\ (qo/qi) * (qo/qi) * (qo/qi))) * \text{study area acres} * 43560.17/12$

Variable Definitions

P = Average rainfall for a 24-hour period (inches)
Am = Study area acres/640 to determine square miles
Fp = Swamp pond percentage adjustment factor
qo = Existing peak flow condition with trees
qi = Peak flow without trees
C_0 = TR-55 coefficents in accordance with raintype

Output Values

Peak = Peak Flow (cfs)
Vs = Storage volume (cubic feet)
Vr = Runoff volume (inches)
CN = Runoff curve number (weighted)
Q = Runoff (inches)
F = Flow length (feet)
S = Potential maximum retention after runoff begins (inches)
L = Lag time (hours)
Tc = Time of concentration (hours)
qu = Unit peak discharge (csm/inches)

TR-55 formulas are used in most engineering firms, soil conservation districts, and municipalities around the country. As of 1994, more than 300,000 copies of the TR-55 manual have been sold by the U.S. National Technical Information Service. The NRCS methods used in TR-55 are very effective in evaluating the effects of land-cover/land use changes and conservation practices on direct runoff. For more information about TR-55, see the following website:
www.wcc.nrcs.usda.gov/water/quality/common/tr55/tr55.html

The CITYgreen stormwater runoff analysis is not intended to be used to design stormwater management facilities, culverts, or ditches. The program is used to estimate the effects of vegetation, especially trees, on runoff volume and peak flow. Percent changes in runoff volume and peak flow are determined automatically by comparing two different scenarios for the same site.

References

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Trees and Energy Conservation

Summary

CITYgreen's energy conservation analysis utilizes methods developed by Jill Mahon of AMERICAN FORESTS, interpolated from research by Dr. Greg McPherson of the USDA Forest Service. The program estimates the energy conservation benefits of trees resulting from direct shading of one- and two-story residential buildings.

Trees are most effective when located to shade air conditioners, windows, or walls and when located on the side of the home receiving the most solar exposure (in addition to other criteria). In many parts of the country the west side is most valuable, followed by the east and south, although this ranking can change based on geographical considerations.

CITYgreen assigns each tree an energy rating, 1 through 5, based on location characteristics listed above and information about tree size and shape. For many parts of the country, for instance, a large tree located near the west side of a building and shading an air conditioner or window would be assigned a near-maximum energy rating.

Each tree then is assumed to reduce a home's annual energy bill by a percentage associated with each energy rank, which varies based on the climate being studied. For instance a tree with an energy ranking of 3 in one city might be assumed to reduce an air conditioning bill by 1.2%, but in a more northern city a tree with an energy ranking might be assumed to reduce the bill by only 1%. The percentage savings produced by each tree around a home are multiplied by a home's average annual energy use for air conditioning (input by the user). CITYgreen adds the results together to produce the savings per home, which are in turn summed to estimate savings per site.

Technical Methodology

The program assigns an energy rating (0 = No Savings.....5 = Maximum Savings) to each tree that has been field-verified and inventoried based on the following criteria:

- Distance from residential building structure
- Orientation relative to the building
- Ability to shade a window and/or air conditioner

CITYgreen incorporates research from 11 cities distributed across the United States. Users are asked to identify their region of the U. S.; the program uses data from the nearest of those cities. If data is available from more than one city within that region, the user is asked to identify which is closest to the project location.

Research from the following cities was used: Washington, DC; Tucson, Arizona; Atlanta, Georgia; Denver, Colorado; Boston, Massachusetts; Portland, Oregon; Los Angeles, California; Minneapolis, Minnesota; Dallas, Texas; Chicago, Illinois and Miami, Florida.

The user is prompted to enter the cooling cost associated with running an air conditioner during the summer. This information can be obtained from a local utility company or from the U.S. Department of Energy. Multipliers associated with each energy rating (representing % energy use-reduction) are assigned to each tree. Each home's annual energy use is multiplied by each associated tree's multiplier to produce an estimate of dollar and kilowatt hour savings per household.

Multipliers used in CITYgreen were interpolated from "Modeling Benefits and Costs of Community Tree-Planting in 12 U.S. Cities" and "Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project." Dr. McPherson's research includes savings associated with one- and two-story homes assumed to be roughly 1,500 square feet in size. The program uses an average of the two values for both one- and two story homes, and hence applies to both.

Estimated savings from a 20-year-old, 25-foot-high tree in each region were used as the maximum multiplier. The program disregards any trees located more then 35 feet from a home, under the assumption that they are too far from the home to provide significant shade. Dr. McPherson's research has found that a second tree located in an optimal location provides about 2/3 as much savings as the first. Therefore, when more than one tree is assigned a rating of 5 for a given home, only one tree is assumed to provide the full benefits; the rest are assumed to provide 2/3 of the equivalent of a number 5 energy rating.

References

1. McPherson, E. Gregory, Nowak, David J and Rowan A. Rowntree, eds. 1994. "Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project." Gen. Tech. Rep. NE-186. Radnor, PA: USDA Forest Service, Northeastern Forest Experiment Station.
2. McPherson, Greg, Sacamano, Paul and Steve Wensman. 1993. "Modeling Benefits and Costs of Community Tree-Planting in 12 U.S. Cities." USDA Forest Service.

Avoided Carbon Emissions and Energy Conservation

Summary

Trees remove carbon dioxide from the air through leaves and store carbon in their biomass. Approximately half of a tree's dry weight, in fact, is carbon. For this reason, large-scale tree planting projects are recognized as a legitimate tool in many national carbon-reduction programs.

However, trees provide a secondary carbon-related benefit that can be much more valuable, particularly in urban areas. Research by the USDA Forest Service and others has shown that trees strategically planted to shade homes can reduce air conditioning bills significantly. As a result, local power plants are not required to produce as much electricity and thus emit less pollution, including carbon. In certain areas (urban and suburban areas with high cooling costs) these indirect carbon benefits can be significantly higher than the direct effects of sequestration.

Technical Methodology

The avoided carbon module is based in part on fuel-mix profiles for each state's electricity production. Different states and utility regions produce electricity using very different sources. As a result, production of a kWh of electricity in one state may cause the emission of far more carbon than in a neighboring state because different fuels produce different levels of carbon per kWh.

The module also requires estimates of the amount of carbon produced per fuel source per kWh. Coal is said to produce about a pound of carbon while producing a kWh of electricity. Natural gas produces about .35 of a pound. Nuclear power and renewable sources produce essentially none.

CITYgreen estimates the energy-use reduction (in terms of kilowatt hours) produced by direct tree shade. CITYgreen then uses the information learned in steps one and two to convert the number of kilowatt hours reduced on a given site to the amount of carbon avoided as a result.

For instance, on a given site, assuming:

- CITYgreen estimates 1000 kWh are reduced in a state that uses 50% coal and 50% natural gas to produce electricity
- Carbon avoided would be calculated by:

For the Coal-produced portion:
1,000 x 0.5 x .575 (the coal emission factor)= 287.5

For the Gas-produced portion:
1,000 x 0.5 x .3478 (the gas emission factor)= 173.90
Total: 461.40

The third possible source is petroleum. A complete list of emission factors follows:

Coal:	.575 lbs carbon /kWh
Petroleum:	.5058 lbs carbon /kWh
Gas:	.3478 lbs carbon/ kWh

(from Carbon Dioxide Emissions from the Generation of Electric Power in the United States, October 15, 1999 Department of Energy, Environmental Protection Agency.http://www.eia.doe.gov/cneaf/electricity/page/other/co2report.html#electric)

References

1. Department of Energy, Energy Information Administration. 1998, "Electricity at a Glance: State Profiles." (http://www.eia.doe.gov/cneaf/electricity/st_profiles/toc.html)
2. Department of Energy, Energy Information Administration. October 15, 1999. "Carbon Dioxide Emissions from the Generation of Electric Power in the United States." (*http://www.eia.doe.gov/cneaf/electricity/page/other/co2report.html#electric)*

Cool Roofs and Energy Conservation

Summary

CITYgreen's energy conservation analysis includes estimates of the impacts of different colored asphalt shingles on energy use. Research has shown that roof products that reflect the sun's heat back into the atmosphere impose lower cooling costs on buildings than roof products that absorb the sun's heat slowly and release it. Reflectance, or albedo, is often higher in lighter-colored products, although the use of certain materials can make a dark-colored roof more reflective. Scientists from the Department of Energy have completed a considerable amount of research in this area, particularly by the Lawrence Berkeley Laboratories (LBL), the Florida Solar Energy Center, and others.

CITYgreen estimates the energy savings in the homes on a given site compared to a scenario under which all the homes are roofed with black shingles. The difference is reported in terms of dollars and kilowatt hours. As is the case with trees and energy conservation module, the user is asked to input average annual expenditure on air conditioning. Color of the existing shingle roof is gathered during site surveying, which is then associated with an albedo value. If the true albedo value is known, it can be used instead. The energy-related impacts of different roof products vary according to a number of factors, including insulation levels, heat system used, geographical location, and climate. Lawrence Berkeley Laboratories has estimated associated savings in 17 U.S. cities. The user is asked to identify the nearest city and results from that city are used.

Technical Methodology

CITYgreen assumes albedo values for Black, Dark Gray, Light Gray and White asphalt shingles on the basis of research conducted by the Urban Heat Island Project from the Environmental Energy Technologies Division of the Department of Energy's Lawrence Berkeley Laboratories. These values were obtained from the following web page: *http://eetd.lbl.gov/HeatIsland/*

LBL research on the impacts of different roof reflectance in 17 cities was used to compare the impacts of dark gray, light gray and white asphalt roofs to a base case of black. The user is asked to identify their region of the country. If data is available from more than one city within a region, the user is asked to identify the nearest city.

For each city, a multiplier (percent energy-use reduction) is associated with each color. Each multiplier also varies according to the home's estimated R-value (insulation levels) and according to the heating system (heat pump or gas furnace).

Research from the following cities was used: Albuquerque, New Mexico; Atlanta, Georgia; Austin, Texas; Dallas/Ft Worth, Texas; Houston, Texas; Las Vegas, Nevada; Lexington, Kentucky; Burbank, California; Long Beach, California; Nashville, Tennessee; Tampa, Florida; Phoenix, Arizona; Raleigh, North Carolina; Sacramento, California; Salt Lake City, Utah; Tucson, Arizona; and Sterling, Virginia.

To calculate savings per home, the multiplier is multiplied by the average annual cooling cost per home. The results for each home can be summed to produce savings per site.

The Cool Roof module applies only to single-family residences one and two stories tall, with asphalt shingle roofs. It is meant to provide and estimate only, based on a limited amount of information gathered about each home. For information and research results about the impacts of different roofing products on energy use, and the use of shade trees for energy conservation, see the website of LBL's Environmental Energy Technologies Division at *http://eetd.lbl.gov/*

References

For Albedo Values: The Cool Roofing Materials Database web page of the Environmental Energy Technologies Division of the Department of Energy's Lawrence Berkeley Laboratories: *http://eetd.lbl.gov/CoolRoof/*

For % savings associated with more reflective (non-black asphalt shingles): Research results from 17 cities provided to AMERICAN FORESTS by Dr. Hashed Akbari, Group Leader, Heat Island Group, Lawrence Berkeley Laboratories, September, 1998.

Tree Growth Model

CITYgreen's tree growth model was developed by AMERICAN FORESTS. The program "grows" the tree diameter-at-breast height (D.B.H.), the tree height, and the tree canopy according to species and year of growth selected. CITYgreen also considers the area of the country your project is in, since trees grow at different rates. The user will choose from Northeast, Mid-Atlantic, Southeast, Midwest, Southwest, Mountain and Pacific Northwest, or the default Mainland US. Currently, 264 trees are supported by the growth model program. The program uses the following method, derived from Nowak, Susinni, Stevens, and Luley, to estimate growth:

Tree Growth Rate	*Trunk Diameter (Inches/Year)*	*Height (Inches/Year)*
Slow-Growing Trees	0.1	1.0
Medium-Growing Trees	0.25	1.5
Fast-Growing Trees	0.5	3.0

The height change is determined by multiplying the number of growth years by the height growth rate. The diameter (dbh) change is projected by adding the existing diameter (inches) to the number of growth years multiplied by the diameter growth rate.

A growth factor was derived for individual tree species based on diameter and canopy area trends taken from AMERICAN FORESTS' composite tree species database of more than 13,000 trees. This growth factor is multiplied by the calculated diameter growth for each species to estimate canopy radius and canopy area in square feet. By looking at the largest inventoried specimen from each species, a maximum potential growth has been determined for 264 (nearly all) tree species in the CITYgreen species database**.** The Canopy Growth Factor is based on a linear regression of canopy radius divided by diameter.

References

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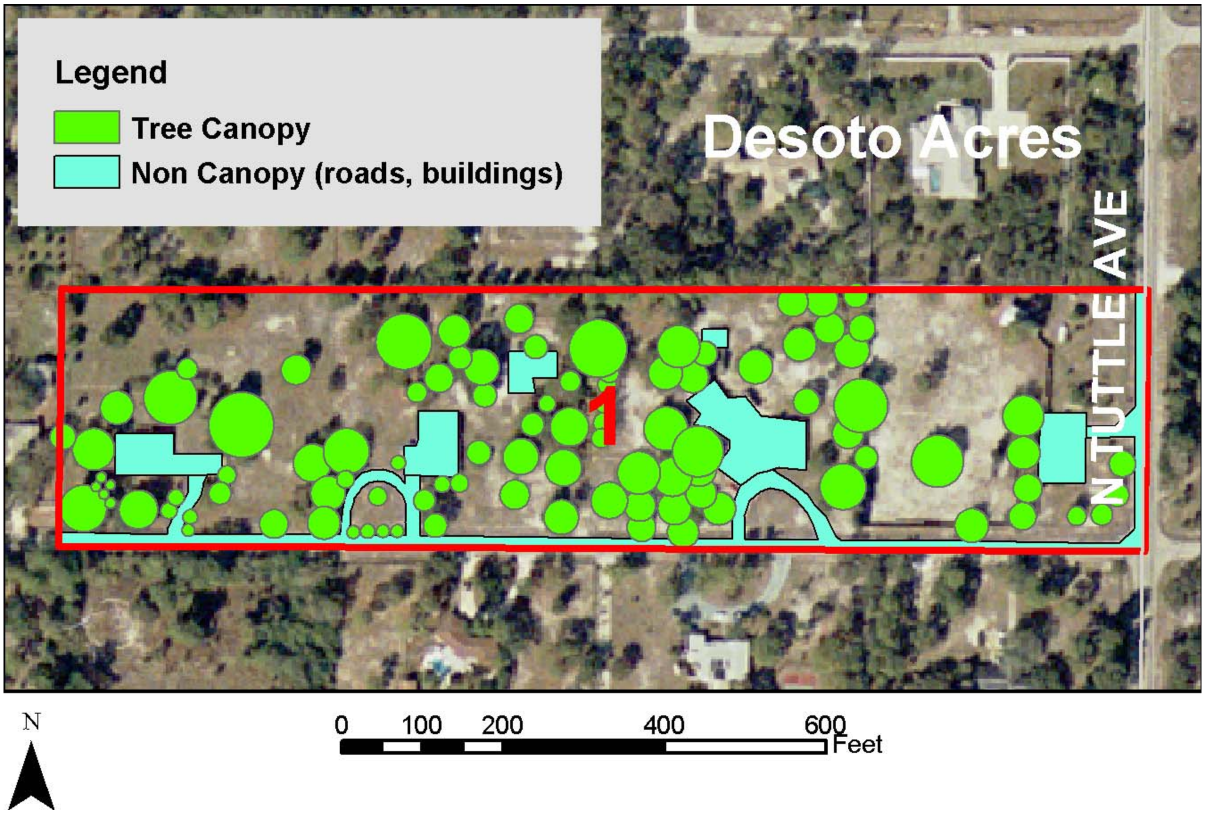
2. Energy Information Administration. "Method for Calculating Carbon Sequestration by Trees in Urban and Suburban Settings," *Voluntary Reporting of Greenhouse Gases*, September 1996. Washington, DC: U.S. Department of Energy,.

Wenger, Karl F., ed. 1984. Forestry Handbook. New York: John Wiley & Sons.

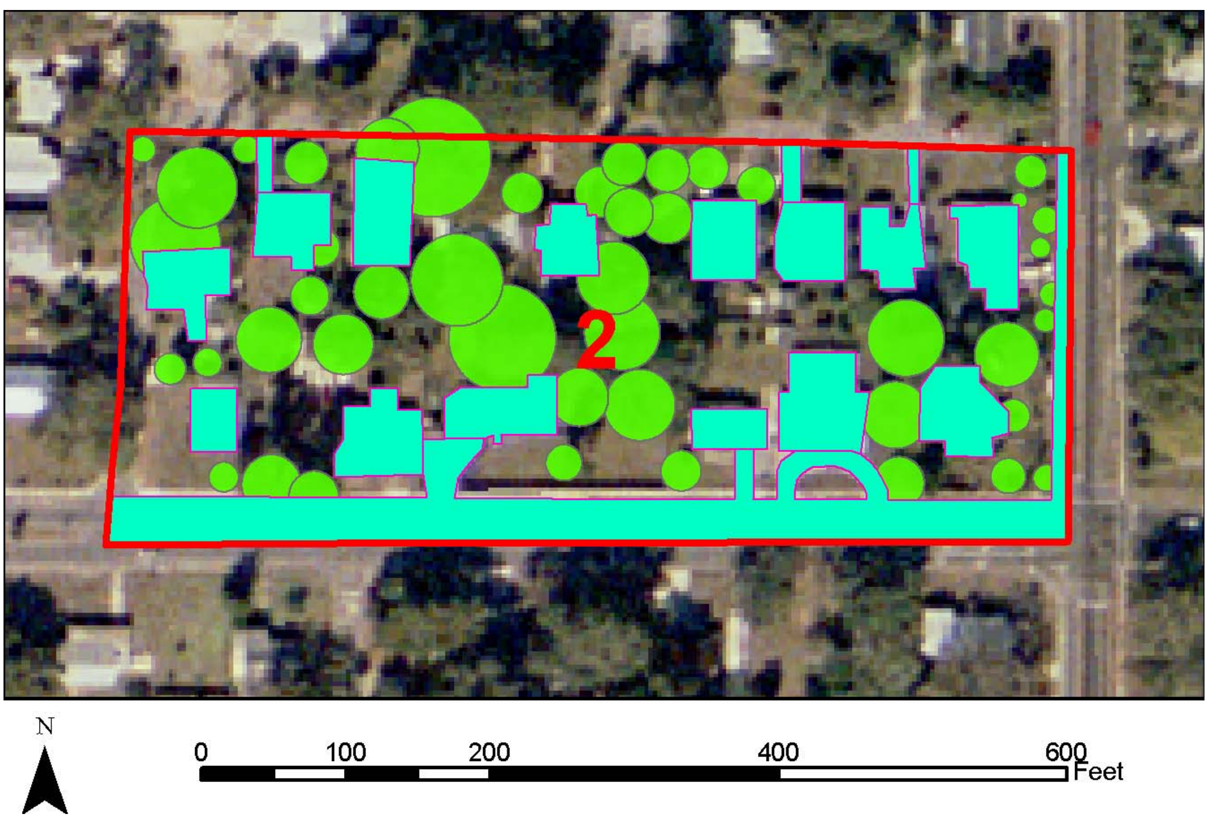
Special acknowledgment to Nina Bassuk, Cornell University; Edward Macie, USDA Forest Service; Mickey Merrit, Texas Forest Service; Phillip Hoefer, Colorado State Forest Service; Gary Moll, AMERICAN FORESTS; and Bob Skiera for regional growth data.

APPENDIX B

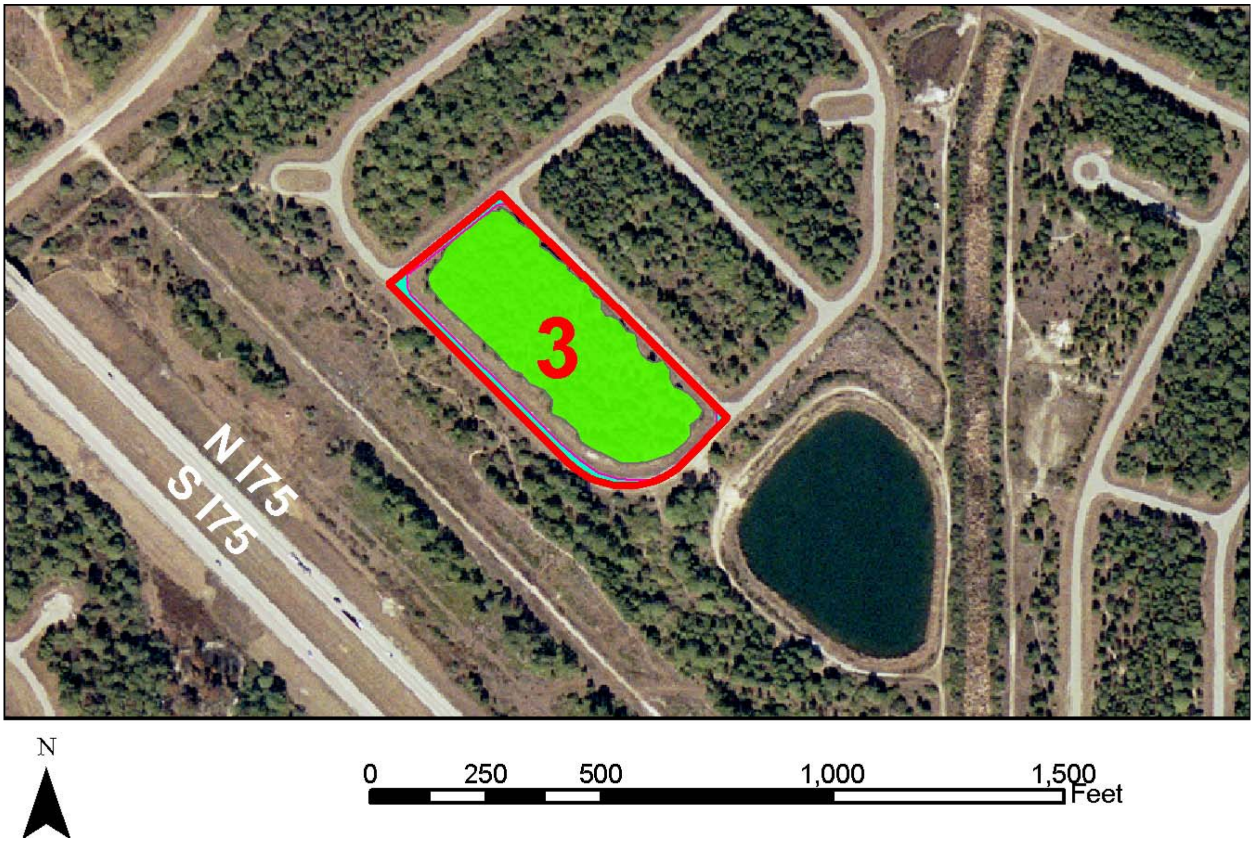
Sarasota County Local Analysis Site Maps

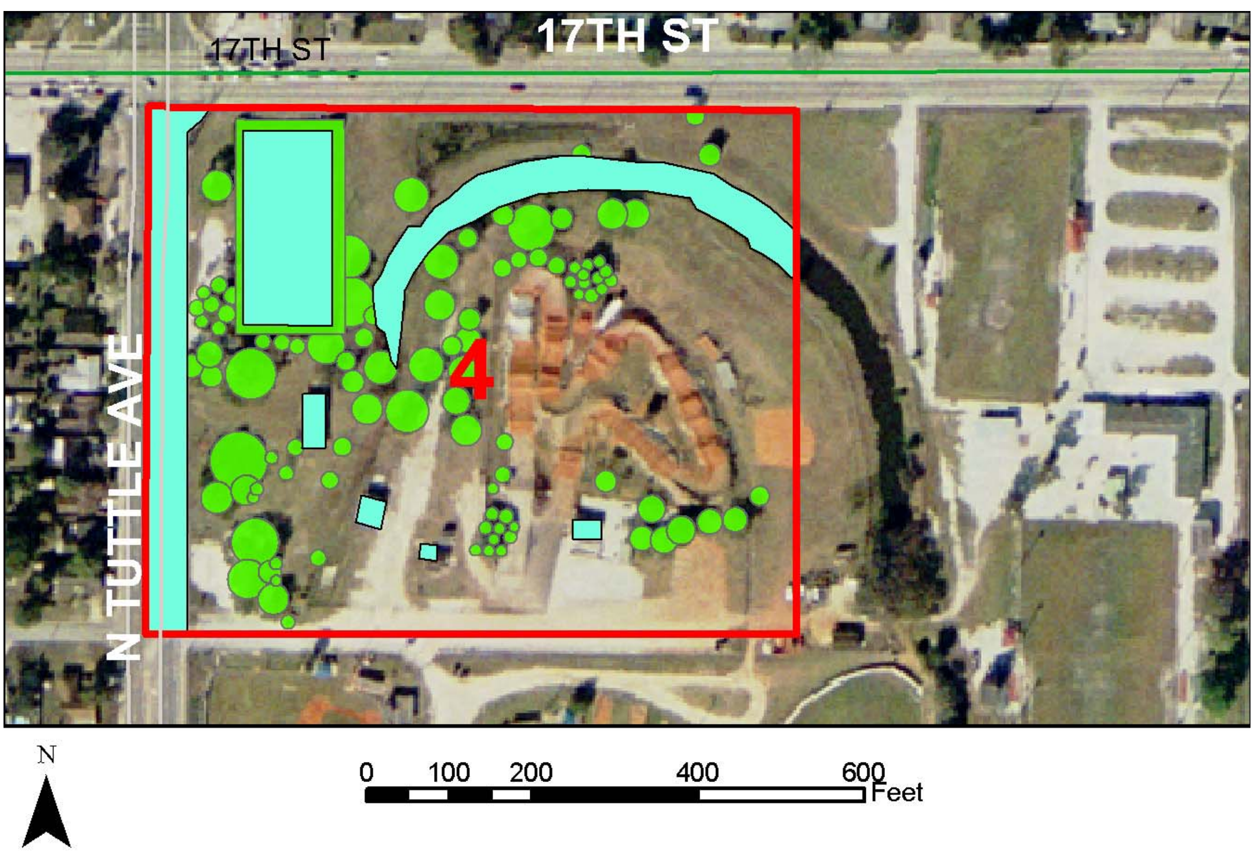


Legend
Tree Canopy
Non Canopy (roads, buildings)
Desoto Acres
N TUTTLE AVE
1
N
0
100
200
400
600
Feet

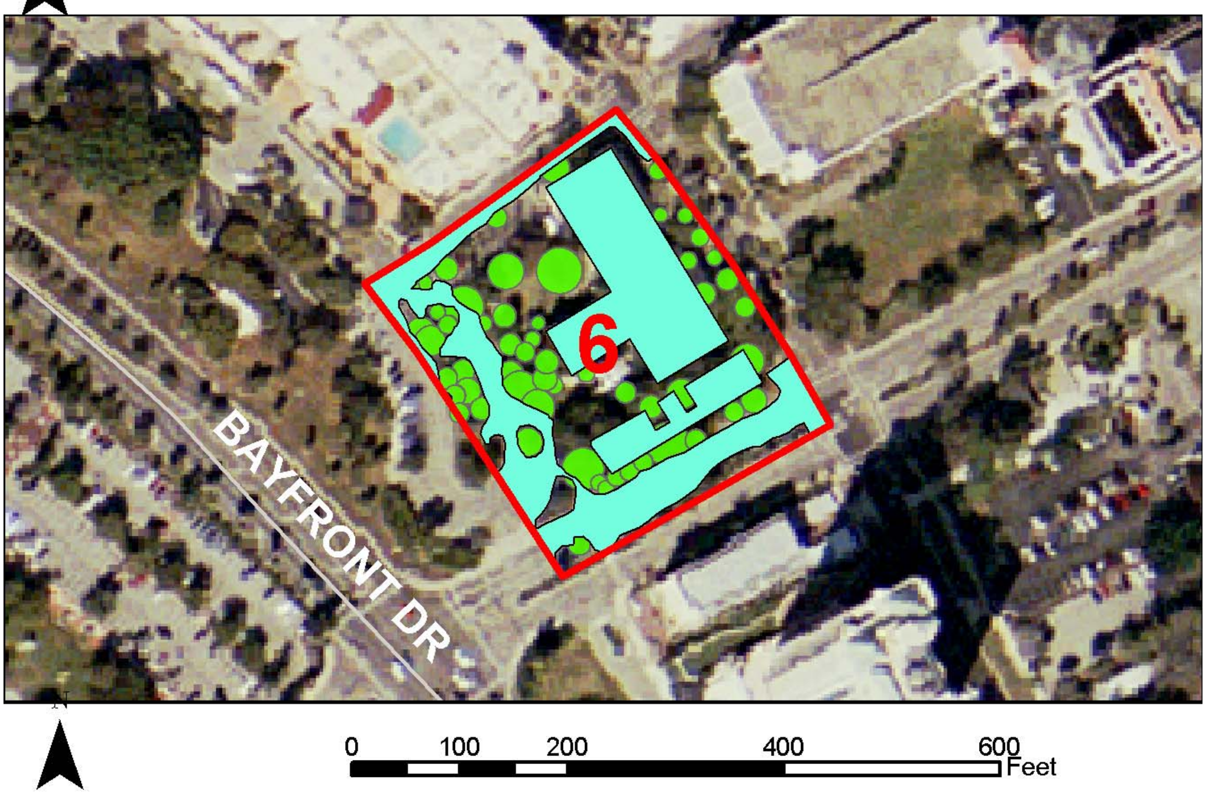


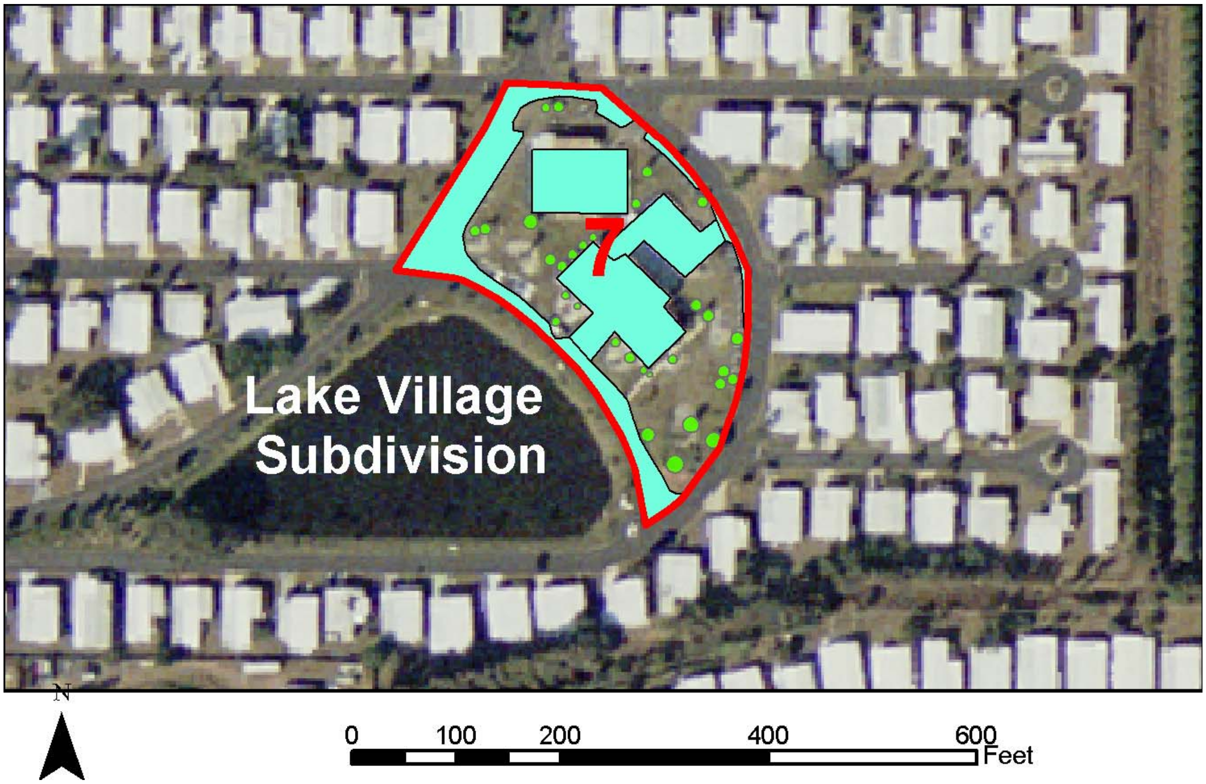
2
N
0
100
200
400
600
Feet

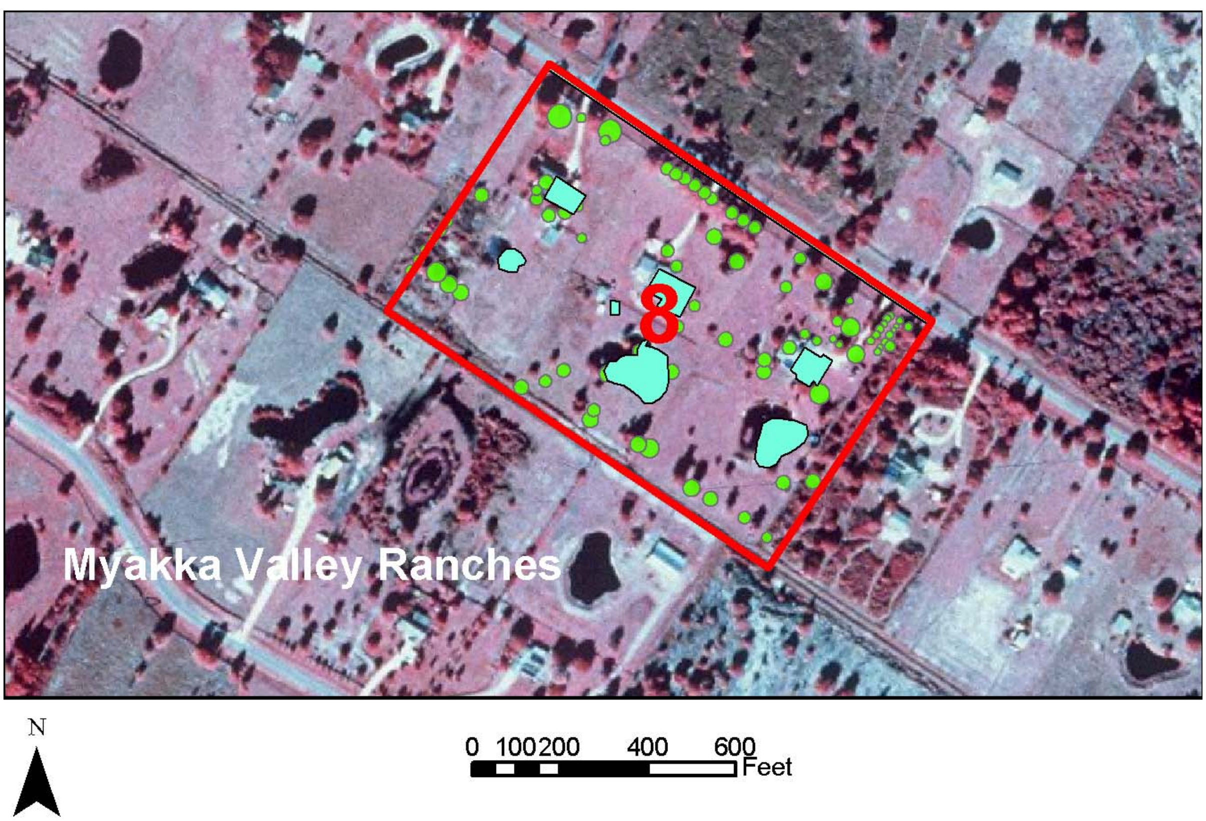

3
N I75
S I75
N
0
250
500
1,000
1,500
Feet

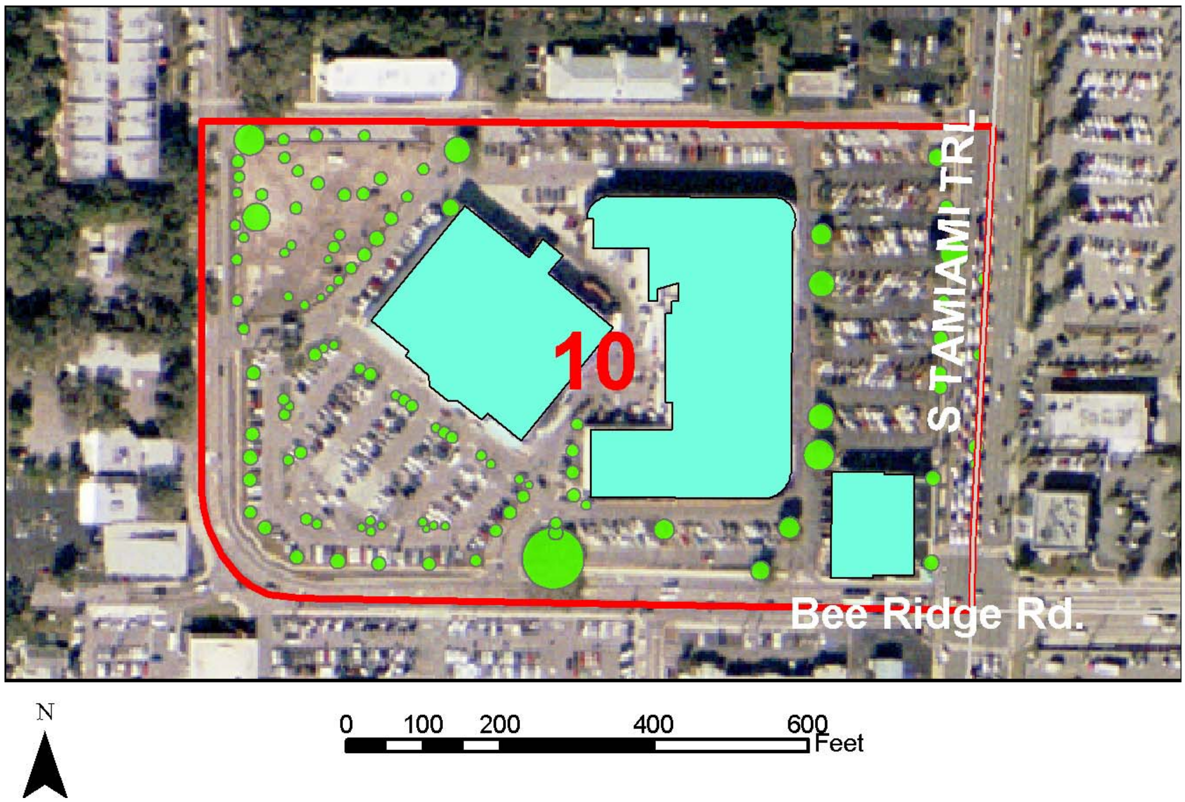

17TH ST
17TH ST
4
N TUTTLE AVE
N
0
100
200
400
600
Feet


5
City Island
N
0 100 200 400 600
Feet


6
BAYFRONT DR
N
0 100 200 400 600
Feet


Lake Village
Subdivision
7
N
0
100
200
400
600
Feet


Myakka Valley Ranches
8
N
0
100
200
400
600
Feet


10
S TAMIAMI TRL
Bee Ridge Rd.
N
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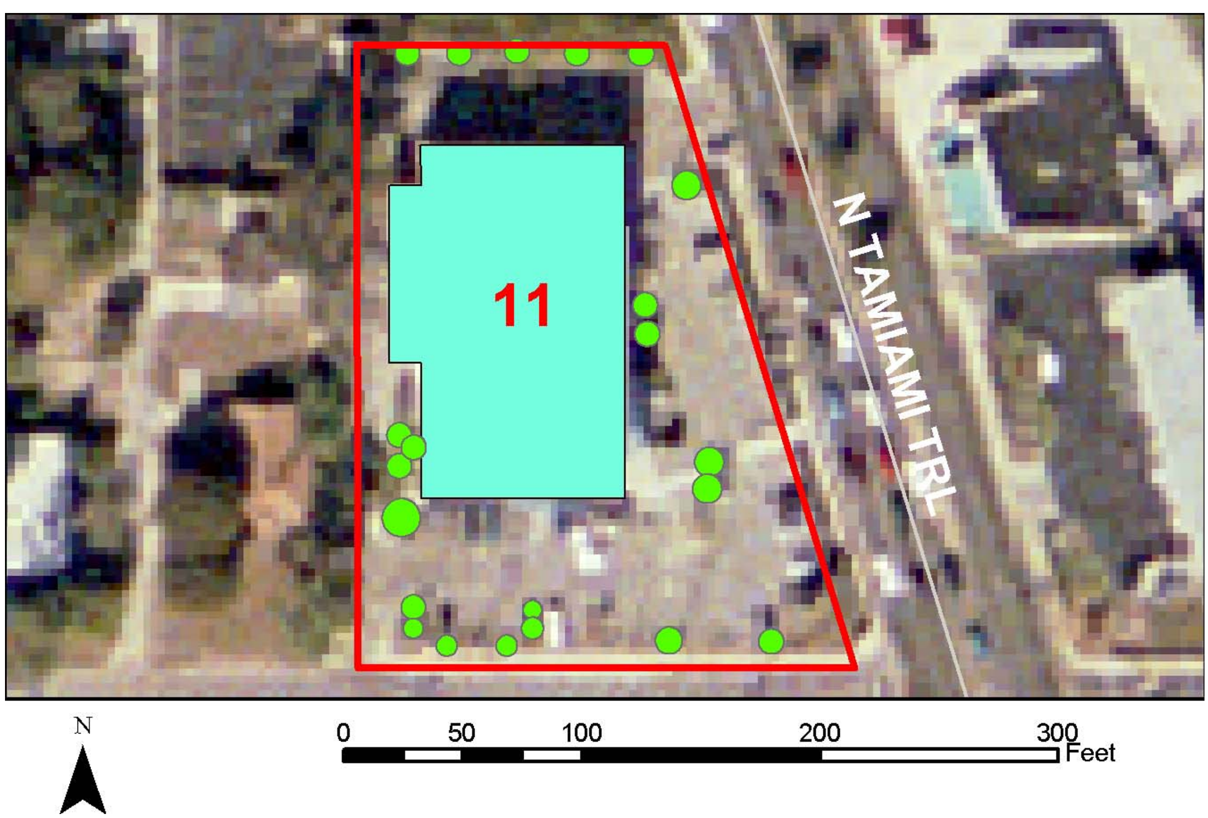
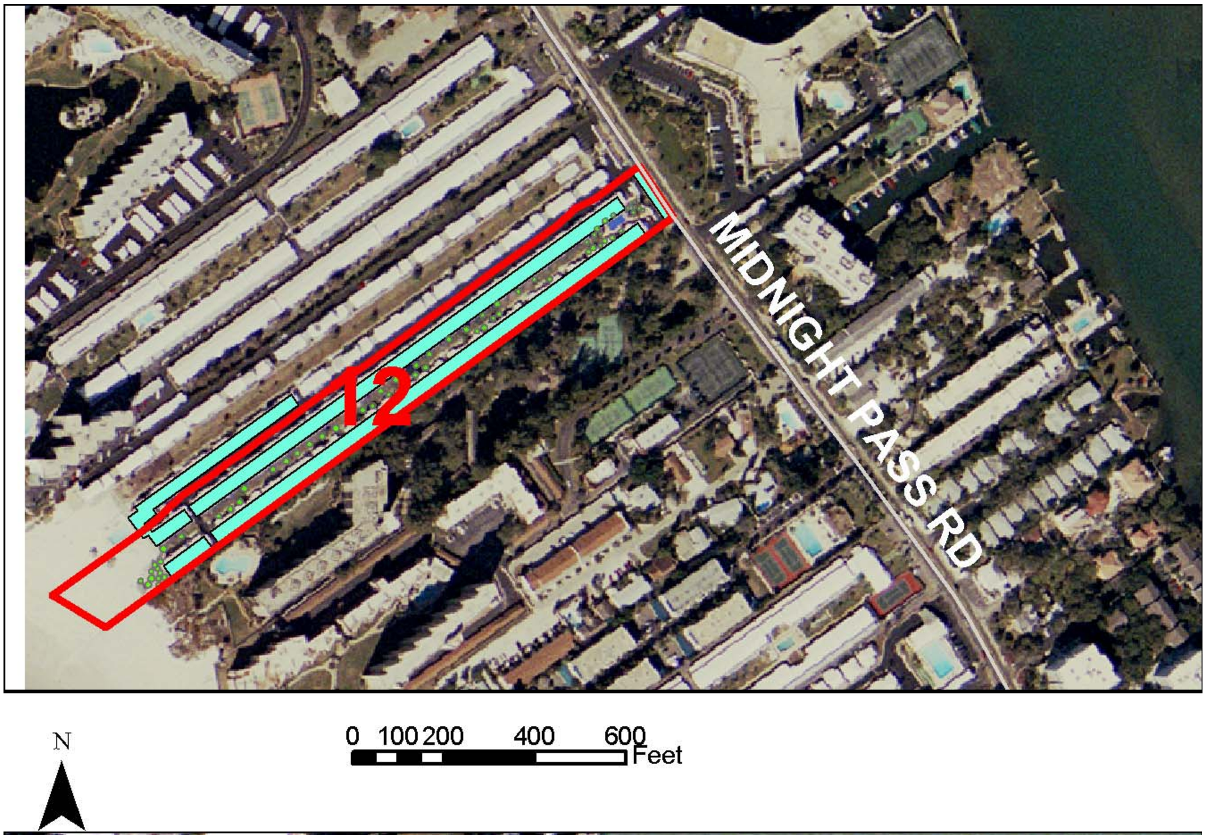
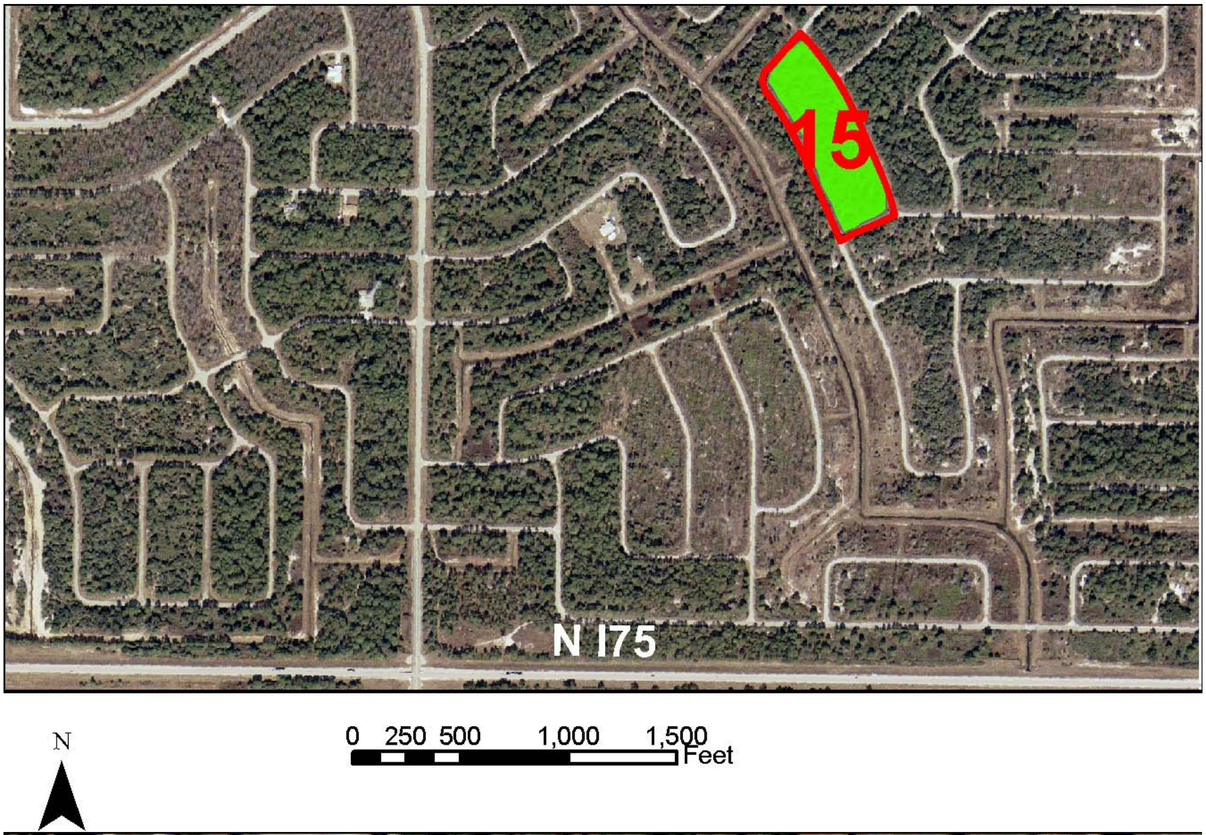
Feet


11
N TAMIAMI TRL
N
0 50 100 200 300
Feet

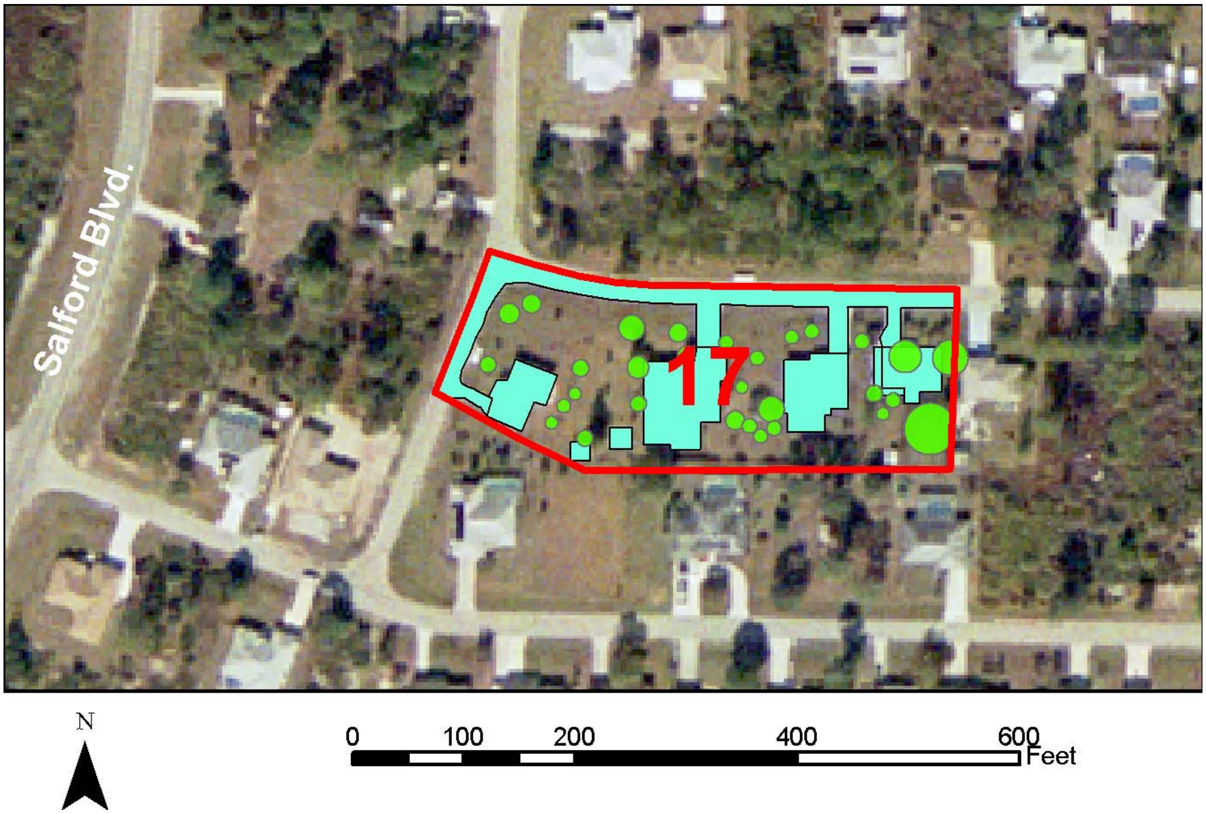


MIDNIGHT PASS RD
12
N
0 100 200 400 600
Feet

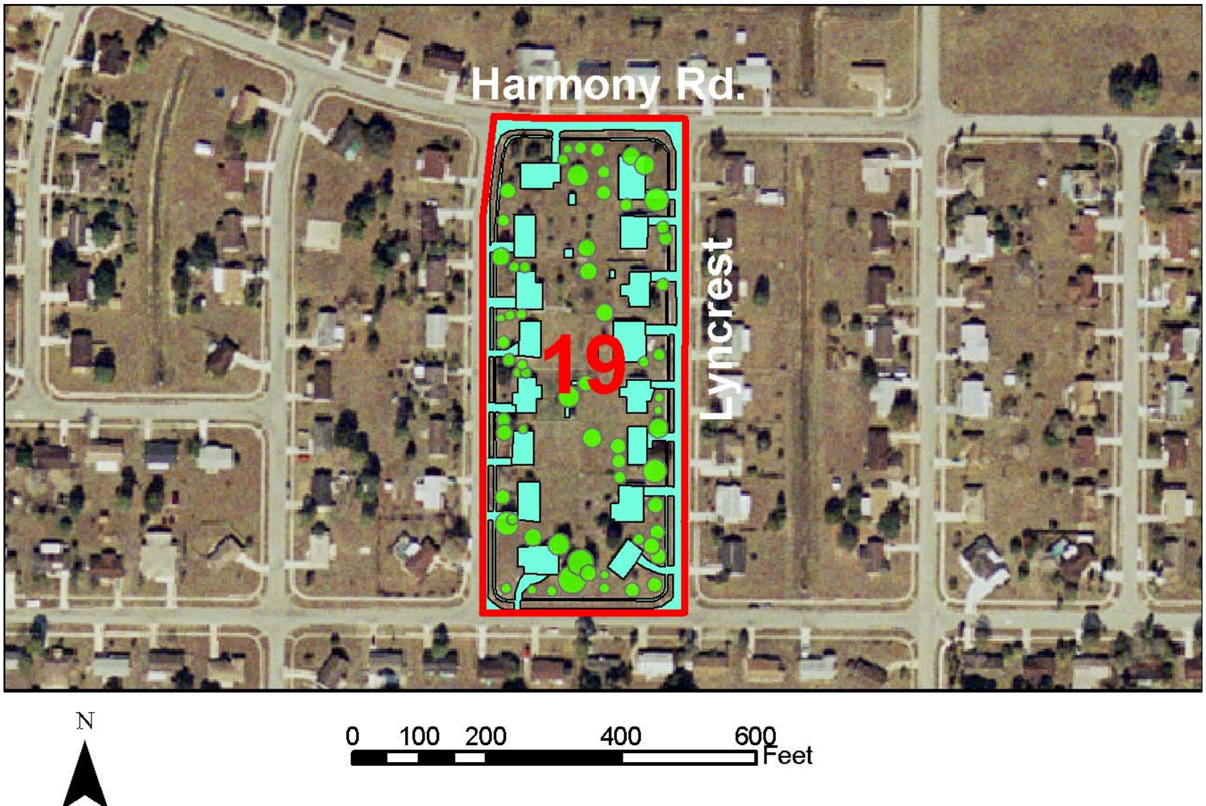
SIESTA DR
14
N
0 100 200 400 600
Feet


15
N I75
N
0 250 500 1,000 1,500
Feet


Bayshore Estates
Park Blvd.
16
N
0 100 200 400 600
Feet


Salford Blvd.
17
N
0
100
200
400
600
Feet


Olympia Rd.
Shamrock Dr.
18
N
0
100
200
400
600
Feet


Harmony Rd.
Lyncrest
19
N
0 100 200 400 600
Feet


Overbrook Rd.
San Remo
20
N
0 100 200 400 600
Feet

APPENDIX C

Vegetation Canopy Coverage Data from Satellite Imagery Analysis

Vegetation Canopy Coverage by Municipality

	Municipality	WATER	LAND	VEGETATION	TOTAL-acre
1975	SARASOTA COUNTY	126	69,604	213,888	283,618
	CITY OF SARASOTA	2	6,378	3,051	9,431
	CITY OF VENICE	34	3,609	3,763	7,407
	TOWN OF LONGBOAT KEY	-	1,071	416	1,487
	CITY OF NORTH PORT	38	24,474	39,398	63,909
	Total-Acre	**200**	**105,136**	**260,516**	**365,851**
1986	SARASOTA COUNTY	697	138,264	144,713	283,674
	CITY OF SARASOTA	59	8,225	1,102	9,386
	CITY OF VENICE	53	5,577	1,767	7,397
	TOWN OF LONGBOAT KEY	51	1,091	322	1,464
	CITY OF NORTH PORT	124	37,382	26,411	63,917
	Total-Acre	**983**	**190,539**	**174,315**	**365,838**
1993	SARASOTA COUNTY	648	135,433	147,576	283,657
	CITY OF SARASOTA	7	8,383	1,014	9,405
	CITY OF VENICE	35	5,080	2,280	7,394
	TOWN OF LONGBOAT KEY	29	1,072	368	1,468
	CITY OF NORTH PORT	66	34,448	29,404	63,918
	Total-Acre	**784**	**184,417**	**180,642**	**365,843**
2002	SARASOTA COUNTY	2,192	138,327	143,156	283,675
	CITY OF SARASOTA	51	7,812	1,549	9,412
	CITY OF VENICE	116	5,934	1,335	7,385
	TOWN OF LONGBOAT KEY	12	1,084	366	1,462
	CITY OF NORTH PORT	288	36,486	27,137	63,911
	Total-Acre	**2,659**	**189,642**	**173,543**	**365,844**

Vegetation Canopy Coverage in east vs. west Sarasota County

	Direction	WATER	**Acre**	LAND	**Acre**	VEGETATION	**Acre**
	EAST OF 75	26400.048	**6.523451861**	160310990.2	**39612.85**	659667894	**163003.9**
1975	WEST OF 75	782101.416	**193.2572599**	265168680	**65523.18**	394634514.3	**97514.19**
	Direction	WATER		LAND		VEGETATION	
	EAST OF 75	1008548.481	**249.2123297**	340865757.1	**84227.93**	478228126.9	**118170.2**
1986	WEST OF 75	2970868.049	**734.1014949**	430243130.2	**106313.1**	227215554.3	**56144.96**
	Direction	WATER		LAND		VEGETATION	
	EAST OF 75	1697611.668	**419.4798432**	328395403.2	**81146.5**	490068625.6	**121096**
1993	WEST OF 75	1476138.638	**364.7538574**	417935277.7	**103271.8**	240978326.8	**59545.74**
	Direction	WATER		LAND		VEGETATION	
	EAST OF 75	5414458.5	**1337.912695**	338956798.5	**83756.22**	475750257.8	**117557.9**
2002	WEST OF 75	5345417.25	**1320.852602**	428515483.5	**105886.2**	226576325.3	**55987.01**

Summary of Vegetation Canopy by Land Use

Year	Flucsdesc	WATER	LAND	VEG.	Total Acres
1975	BAYS AND ESTUARIES	67.68	1296.54	734.70	2098.92
	RESERVOIRS	1.63	1906.48	4130.16	6038.27
	MANGROVE SWAMPS	22.83	433.81	237.29	693.93
	FRESHWATER MARSHES	1.63	7144.81	27590.94	34737.38
	EMERGENT AQUATIC VEGETATION	81.54	350.64	802.38	1234.56
	WET PRAIRIES	0.00	1327.52	5582.44	6909.97
	LAKES	319.65	1086.97	1409.07	2815.68
	SHRUB AND BRUSHLAND	0.00	9175.23	30717.30	39892.54
	HARDWOOD CONIFER MIXED	10.60	2261.19	10825.67	13097.46
	SALTWATER MARSHES	13.86	397.12	587.93	998.90
	CROPLAND AND PASTURELAND	0.00	7811.83	39448.94	47260.78
	OPEN LAND	22.83	10552.50	15252.65	25827.98
	STREAM AND LAKE SWAMPS (BOTTOMLAND)	10.60	2739.03	16399.96	19149.59
	RECREATIONAL	12.23	2638.74	5362.28	8013.25
	STREAMS AND WATERWAYS	0.00	347.37	798.31	1145.68
	RESIDENTIAL LOW DENSITY < 2 DWELLING UNITS	2.45	6911.60	14686.74	21600.78
	RESIDENTIAL HIGH DENSITY	46.48	8619.93	7801.23	16467.64
	PINE FLATWOODS	22.02	14073.53	37720.23	51815.78
	INDUSTRIAL	0.00	1074.74	687.41	1762.15
	MIXED RANGELAND	0.00	327.80	1351.17	1678.97
	WETLAND FORESTED MIXED	0.00	430.55	1795.58	2226.13
	TIDAL FLATS/SUBMERGED SHALLOW PLATFORM	3.26	13.05	5.71	22.02
	INTERMITTENT PONDS	0.00	14.68	47.30	61.97
	RESIDENTIAL MED DENSITY 2->5 DWELLING UNIT	27.72	13939.80	15450.80	29418.32
	UTILITIES	0.00	911.65	1989.65	2901.31
	COMMERCIAL AND SERVICES	1.63	3933.64	2168.23	6103.50
	INSTITUTIONAL	0.00	930.41	1197.05	2127.46
	HERBACEOUS	0.00	236.48	910.84	1147.31
	TRANSPORTATION	0.00	2048.36	2182.91	4231.27
	WETLAND CONIFEROUS FORESTS	0.00	72.57	260.12	332.70
	UPLAND HARDWOOD FORESTS - PART 1	1.63	344.11	1946.43	2292.18
	WETLAND HARDWOOD FORESTS	0.00	30.17	26.91	57.08
	UPLAND CONIFEROUS FOREST	0.00	257.68	682.52	940.19
	NURSERIES AND VINEYARDS	0.00	105.19	237.29	342.48
	DISTURBED LAND	0.00	123.13	256.86	379.99
	TREE CROPS	0.00	504.75	3257.65	3762.40
	BAY SWAMPS	0.00	59.53	257.68	317.20
	CYPRESS	0.00	72.57	601.79	674.36
	ROW CROPS	0.00	876.59	1978.24	2854.83
	BEACHES OTHER THAN SWIMMING BEACHES	0.00	51.37	5.71	57.08
	OTHER OPEN LANDS <RURAL>	0.00	678.44	1962.74	2641.18

	TREE PLANTATIONS	0.00	65.23	454.20	519.43
	COMMUNICATIONS	0.00	26.91	61.97	88.88
	EXTRACTIVE	0.00	975.26	1907.29	2882.55
	SPECIALTY FARMS	0.00	98.67	400.38	499.04
	LONGLEAF PINE - XERIC OAK	0.00	3.26	0.00	3.26
	FEEDING OPERATIONS	0.00	0.00	12.23	12.23
	Total-Acre	**670.28**	**107281.43**	**262184.87**	**370136.58**
1986	BAYS AND ESTUARIES	496.57	1368.41	223.73	2088.71
	RESERVOIRS	331.49	3879.91	1823.31	6034.71
	MANGROVE SWAMPS	35.30	376.61	290.88	702.78
	FRESHWATER MARSHES	42.20	19342.22	15421.44	34805.86
	EMERGENT AQUATIC VEGETATION	101.91	719.50	419.33	1240.75
	WET PRAIRIES	2.65	3020.01	3925.03	6947.69
	LAKES	528.68	1686.10	621.84	2836.61
	SHRUB AND BRUSHLAND	16.45	15743.37	24025.24	39785.06
	HARDWOOD CONIFER MIXED	5.84	2739.21	10343.51	13088.56
	SALTWATER MARSHES	25.21	788.24	202.50	1015.96
	CROPLAND AND PASTURELAND	5.84	23814.77	23311.04	47131.65
	OPEN LAND	12.47	16733.32	9129.03	25874.82
	STREAM AND LAKE SWAMPS (BOTTOMLAND)	6.64	2289.36	16849.57	19145.56
	RECREATIONAL	194.54	4039.15	3739.25	7972.94
	STREAMS AND WATERWAYS	15.39	738.61	387.49	1141.49
	RESIDENTIAL LOW DENSITY < 2 DWELLING UNITS	8.23	13435.44	8173.05	21616.71
	RESIDENTIAL HIGH DENSITY	22.29	14251.55	2110.74	16384.58
	PINE FLATWOODS	10.35	17561.91	34285.14	51857.40
	INDUSTRIAL	13.80	1561.89	160.30	1735.99
	MIXED RANGELAND	0.53	577.25	1104.34	1682.12
	WETLAND FORESTED MIXED	1.06	636.43	1591.61	2229.11
	TIDAL FLATS/SUBMERGED SHALLOW PLATFORM	12.74	13.27	3.45	29.46
	INTERMITTENT PONDS	0.27	56.27	8.76	65.29
	RESIDENTIAL MED DENSITY 2->5 DWELLING UNIT	44.85	24794.64	4602.07	29441.56
	UTILITIES	1.86	1831.80	1021.80	2855.46
	COMMERCIAL AND SERVICES	32.11	5362.18	709.95	6104.24
	INSTITUTIONAL	2.92	1790.40	337.59	2130.91
	HERBACEOUS	0.27	570.35	587.33	1157.95
	TRANSPORTATION	8.49	3496.40	771.52	4276.42
	WETLAND CONIFEROUS FORESTS	0.00	115.18	225.59	340.78
	UPLAND HARDWOOD FORESTS - PART 1	0.27	422.25	1915.67	2338.19
	WETLAND HARDWOOD FORESTS	0.00	20.17	37.95	58.12
	UPLAND CONIFEROUS FOREST	0.00	465.78	444.81	910.59
	NURSERIES AND VINEYARDS	0.27	241.52	105.10	346.88
	DISTURBED LAND	0.27	262.75	119.43	382.44
	TREE CROPS	1.86	1760.41	2008.03	3770.30
	BAY SWAMPS	0.00	76.70	242.84	319.54
	CYPRESS	0.00	43.00	638.03	681.02

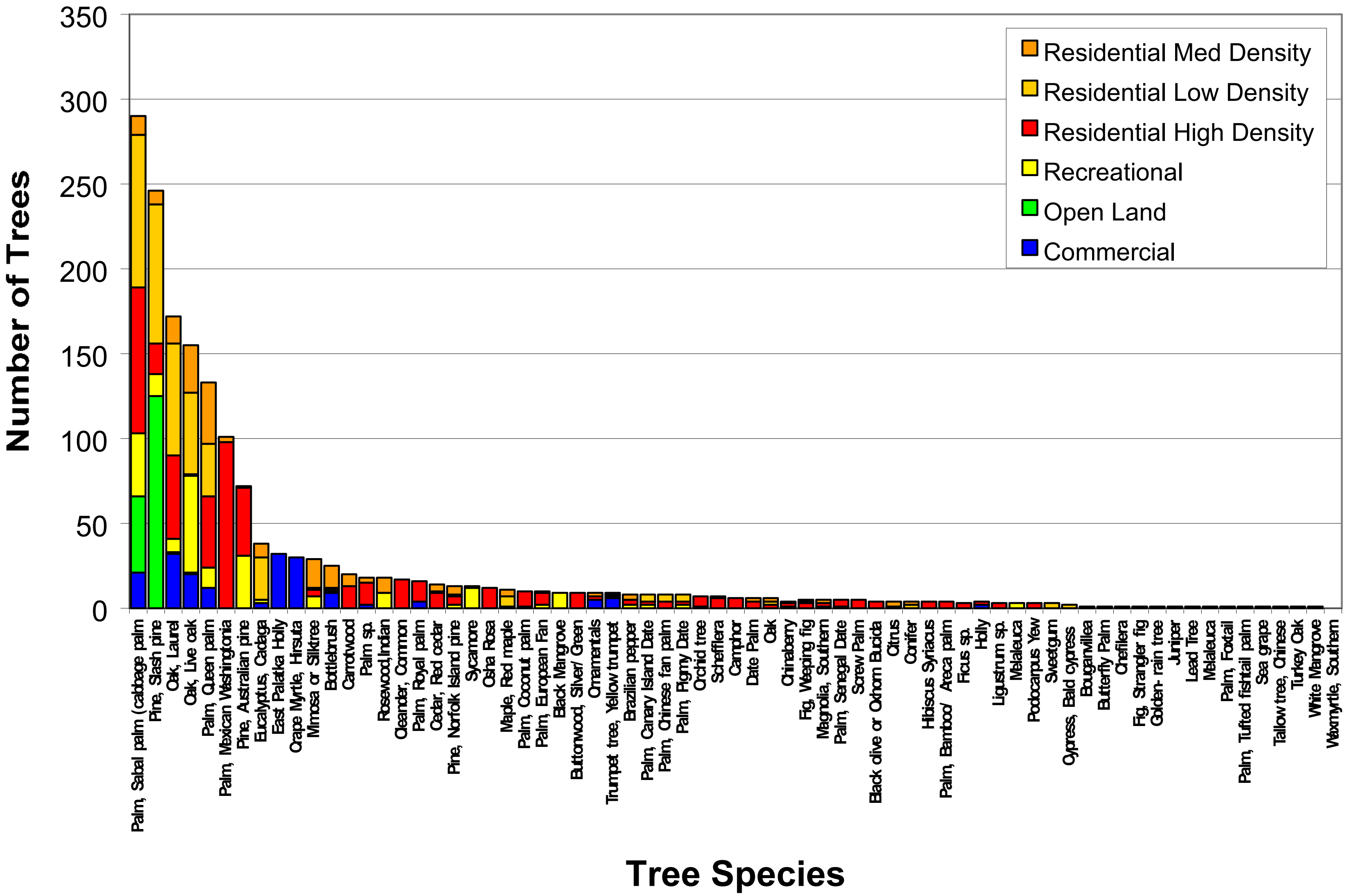
	ROW CROPS	0.00	1913.55	938.99	2852.54
	BEACHES OTHER THAN SWIMMING BEACHES	33.97	25.48	0.00	59.45
	OTHER OPEN LANDS <RURAL>	0.00	1491.56	1146.27	2637.83
	TREE PLANTATIONS	0.00	415.09	113.06	528.15
	COMMUNICATIONS	0.00	69.54	15.66	85.19
	EXTRACTIVE	87.32	2097.74	718.97	2904.03
	SPECIALTY FARMS	0.00	384.57	103.51	488.07
	LONGLEAF PINE - XERIC OAK	0.27	2.39	0.27	2.92
	FEEDING OPERATIONS	0.00	11.68	1.33	13.00
	Total-Acre	**2105.17**	**193037.91**	**174956.34**	**370099.42**
1993	BAYS AND ESTUARIES	303.32	1593.77	178.89	2075.97
	RESERVOIRS	356.75	3926.33	1758.20	6041.28
	MANGROVE SWAMPS	3.10	290.41	409.67	703.18
	FRESHWATER MARSHES	11.10	19333.25	15447.96	34792.30
	EMERGENT AQUATIC VEGETATION	85.96	679.94	478.08	1243.98
	WET PRAIRIES	0.77	3608.04	3363.84	6972.66
	LAKES	585.46	1608.74	653.61	2847.82
	SHRUB AND BRUSHLAND	1.29	17302.45	22512.26	39815.99
	HARDWOOD CONIFER MIXED	0.26	1979.43	11104.21	13083.90
	SALTWATER MARSHES	1.03	711.70	297.12	1009.85
	CROPLAND AND PASTURELAND	1.55	24238.45	22916.51	47156.50
	OPEN LAND	4.39	15090.17	10754.95	25849.51
	STREAM AND LAKE SWAMPS (BOTTOMLAND)	0.26	1503.93	17595.95	19100.14
	RECREATIONAL	35.62	2666.60	5297.58	7999.80
	STREAMS AND WATERWAYS	8.26	688.46	438.32	1135.05
	RESIDENTIAL LOW DENSITY < 2 DWELLING UNITS	1.55	11004.57	10579.67	21585.79
	RESIDENTIAL HIGH DENSITY	4.65	15490.81	922.60	16418.05
	PINE FLATWOODS	0.52	14443.53	37371.14	51815.18
	INDUSTRIAL	1.81	1677.40	68.92	1748.13
	MIXED RANGELAND	0.00	685.11	1006.75	1691.86
	WETLAND FORESTED MIXED	0.00	316.74	1920.57	2237.31
	TIDAL FLATS/SUBMERGED SHALLOW PLATFORM	10.58	15.23	3.61	29.43
	INTERMITTENT PONDS	0.00	54.47	11.36	65.83
	RESIDENTIAL MED DENSITY 2->5 DWELLING UNIT	4.39	24910.13	4536.32	29450.84
	UTILITIES	1.55	2088.62	785.52	2875.70
	COMMERCIAL AND SERVICES	9.55	5681.69	400.64	6091.88
	INSTITUTIONAL	0.52	1862.49	261.24	2124.25
	HERBACEOUS	0.00	760.23	384.63	1144.86
	TRANSPORTATION	2.07	3911.36	375.34	4288.76
	WETLAND CONIFEROUS FORESTS	0.00	87.25	249.88	337.13
	UPLAND HARDWOOD FORESTS - PART 1	0.00	353.14	1977.62	2330.76
	WETLAND HARDWOOD FORESTS	0.00	16.52	43.37	59.89
	UPLAND CONIFEROUS FOREST	0.00	228.46	688.21	916.66
	NURSERIES AND VINEYARDS	0.00	220.45	120.29	340.75
	DISTURBED LAND	0.26	264.08	123.39	387.73

	TREE CROPS	0.00	1310.58	2429.11	3739.70
	BAY SWAMPS	0.00	63.76	256.59	320.35
	CYPRESS	0.00	25.30	669.62	694.92
	ROW CROPS	0.00	1708.38	1123.43	2831.81
	BEACHES OTHER THAN SWIMMING BEACHES	15.23	42.34	0.00	57.57
	OTHER OPEN LANDS <RURAL>	0.00	1761.04	886.46	2647.50
	TREE PLANTATIONS	0.00	200.83	330.94	531.77
	COMMUNICATIONS	0.00	65.83	19.88	85.70
	EXTRACTIVE	300.48	2154.96	444.26	2899.70
	SPECIALTY FARMS	0.00	268.73	224.84	493.57
	LONGLEAF PINE - XERIC OAK	0.00	2.58	0.52	3.10
	FEEDING OPERATIONS	0.00	9.29	4.65	13.94
	Total-Acre	**1752.26**	**186907.57**	**181428.52**	**370088.35**
2002	BAYS AND ESTUARIES	683.61	1206.65	171.81	2062.06
	RESERVOIRS	1090.84	4055.89	917.63	6064.36
	MANGROVE SWAMPS	8.83	230.21	464.24	703.28
	FRESHWATER MARSHES	22.28	20522.49	14257.02	34801.79
	EMERGENT AQUATIC VEGETATION	80.88	694.04	461.43	1236.35
	WET PRAIRIES	2.01	3005.19	3994.47	7001.66
	LAKES	1007.75	1542.03	296.04	2845.82
	SHRUB AND BRUSHLAND	35.12	18916.83	20856.67	39808.62
	HARDWOOD CONIFER MIXED	2.41	2639.30	10447.60	13089.31
	SALTWATER MARSHES	10.84	753.45	252.29	1016.58
	CROPLAND AND PASTURELAND	15.45	23945.55	23175.63	47136.64
	OPEN LAND	42.15	16054.15	9751.75	25848.05
	STREAM AND LAKE SWAMPS (BOTTOMLAND)	1.61	1598.83	17482.58	19083.02
	RECREATIONAL	65.03	2986.52	4927.76	7979.31
	STREAMS AND WATERWAYS	24.08	733.18	374.32	1131.59
	RESIDENTIAL LOW DENSITY < 2 DWELLING UNITS	6.22	12486.58	9132.37	21625.17
	RESIDENTIAL HIGH DENSITY	48.97	15013.89	1342.93	16405.79
	PINE FLATWOODS	28.90	16400.37	35397.48	51826.76
	INDUSTRIAL	33.92	1611.88	86.50	1732.30
	MIXED RANGELAND	0.00	407.44	1277.30	1684.73
	WETLAND FORESTED MIXED	0.40	314.71	1915.35	2230.46
	TIDAL FLATS/SUBMERGED SHALLOW PLATFORM	9.83	15.05	3.41	28.30
	INTERMITTENT PONDS	0.20	55.40	8.23	63.82
	RESIDENTIAL MED DENSITY 2->5 DWELLING UNIT	34.32	23737.61	5680.81	29452.75
	UTILITIES	5.82	2354.29	526.05	2886.17
	COMMERCIAL AND SERVICES	68.44	5673.79	341.40	6083.63
	INSTITUTIONAL	9.23	1838.88	267.14	2115.25
	HERBACEOUS	0.00	468.05	694.25	1162.29
	TRANSPORTATION	11.64	3955.73	316.31	4283.69
	WETLAND CONIFEROUS FORESTS	0.00	65.83	268.55	334.38
	UPLAND HARDWOOD FORESTS - PART 1	0.40	435.73	1890.46	2326.60
	WETLAND HARDWOOD FORESTS	0.00	15.25	42.95	58.21

	UPLAND CONIFEROUS FOREST	0.20	494.34	427.10	921.65
	NURSERIES AND VINEYARDS	1.00	237.24	112.40	350.64
	DISTURBED LAND	39.34	302.47	45.76	387.57
	TREE CROPS	1.20	795.60	2947.38	3744.19
	BAY SWAMPS	0.00	58.61	258.91	317.52
	CYPRESS	0.00	31.71	658.32	690.03
	ROW CROPS	2.81	1724.68	1122.55	2850.04
	BEACHES OTHER THAN SWIMMING BEACHES	1.00	56.40	0.40	57.80
	OTHER OPEN LANDS <RURAL>	10.04	1831.45	802.63	2644.11
	TREE PLANTATIONS	2.01	258.11	266.94	527.06
	COMMUNICATIONS	0.40	62.02	24.29	86.71
	EXTRACTIVE	868.86	1719.06	312.70	2900.62
	SPECIALTY FARMS	0.40	331.37	159.76	491.53
	LONGLEAF PINE - XERIC OAK	0.00	2.01	1.00	3.01
	FEEDING OPERATIONS	0.00	10.84	2.41	13.25
	Total-Acre	**4278.47**	**191650.67**	**174165.28**	**370094.43**

APPENDIX D

Local Analysis Tree and CITYgreen Data


Number of Trees
350
300
250
200
150
100
50
0
Residential Med Density
Residential Low Density
Residential High Density
Recreational
Open Land
Commercial
Palm, Sabal palm (cabbage palm
Pine, Slash pine
Oak, Laurel
Oak, Live oak
Palm, Queen palm
Palm, Mexican Washingtonia
Pine, Australian pine
Eucalyptus, Cadaga
East Palatka Holly
Crape Myrtle, Hirsuta
Mimosa or Silktree
Bottlebrush
Carrotwood
Palm sp.
Rosewood,Indian
Oleander, Common
Palm, Royal palm
Cedar, Red cedar
Pine, Norfolk Island pine
Sycamore
Osha Rosa
Maple, Red maple
Palm, Coconut palm
Palm, European Fan
Black Mangrove
Buttonwood, Silver/ Green
Ornamentals
Trumpet tree, Yellow trumpet
Brazilian pepper
Palm, Canary Island Date
Palm, Chinese fan palm
Palm, Pigmy Date
Orchid tree
Schefflera
Camphor
Date Palm
Oak
Chinaberry
Fig, Weeping fig
Magnolia, Southern
Palm, Senegal Date
Screw Palm
Black olive or Oxhorn Bucida
Citrus
Conifer
Hibiscus Syriacus
Palm, Bamboo/ Areca palm
Ficus sp.
Holly
Ligustrum sp.
Melaleuca
Podocarpus Yew
Sweetgum
Cypress, Bald cypress
Bougainvillea
Butterfly Palm
Cheflera
Fig, Strangler fig
Golden- rain tree
Juniper
Lead Tree
Melaleuca
Palm, Foxtail
Palm, Tufted fishtail palm
Sea grape
Tallow tree, Chinese
Turkey Oak
White Mangrove
Waxmyrtle, Southern
Tree Species

Site						Air Pollution Removal					
Site	Type	Area (ac)	#ofTrees	#Trees/Acre	# of Homes	Ozone	SO2	NO2	PM10	CO	Total Pollution Removal Savings
1	Residential Low Density	9.87	99	10	4	$ 251.00	$ 21.00	$ 130.00	$ 156.00	$ 4.00	$ 562.00
2	Residential Med Density	4.23	46	11	14	$ 111.00	$ 9.00	$ 58.00	$ 69.00	$ 2.00	$ 249.00
3	Open Land	4.88	119	24	0	$ 336.00	$ 28.00	$ 174.00	$ 208.00	$ 5.00	$ 751.00
4	Recreational	11.38	99	9	0	$ 147.00	$ 12.00	$ 76.00	$ 91.00	$ 2.00	$ 328.00
5	Recreational	4.87	41	8	0	$ 141.00	$ 12.00	$ 73.00	$ 88.00	$ 2.00	$ 316.00
6	Commercial	2.24	55	25	0	$ 50.00	$ 4.00	$ 26.00	$ 31.00	$ 1.00	$ 112.00
7	Recreational	1.7	31	18	0	$ 7.00	$ 1.00	$ 3.00	$ 4.00	$ -	$ 15.00
8	Residential Low Density	16.3	83	5	3	$ 125.00	$ 10.00	$ 65.00	$ 78.00	$ 2.00	$ 280.00
9	Residential Med Density	n/a									
10	Commercial	14.48	112	8	0	$ 76.00	$ 6.00	$ 40.00	$ 47.00	$ 1.00	$ 170.00
11	Commercial	1.02	25	25		$ 4.00	$ -	$ 2.00	$ 3.00	$ -	$ 9.00
12	Residential High Density	4.79	63	13	0	$ 16.00	$ 1.00	$ 8.00	$ 10.00	$ -	$ 35.00
13	Residential Med Density	n/a									
14	Open Land	0.81	23	28	0	$ 11.00	$ 1.00	$ 6.00	$ 7.00	$ -	$ 25.00
15	Open Land	6.11	300	49	0	$ 510.00	$ 42.00	$ 264.00	$ 316.00	$ 8.00	$ 1,140.00
16	Residential High Density	5.05	58	11	14	$ 98.00	$ 8.00	$ 51.00	$ 61.00	$ 2.00	$ 220.00
17	Residential Low Density	1.66	31	19	4	$ 18.00	$ 1.00	$ 9.00	$ 11.00	$ -	$ 39.00
18	Residential Med Density	6.05	91	15	21	$ 106.00	$ 9.00	$ 55.00	$ 66.00	$ 2.00	$ 238.00
19	Residential Med Density	5.03	64	13	16	$ 59.00	$ 5.00	$ 31.00	$ 37.00	$ 1.00	$ 133.00
20	Residential High Density	6.65	65	10	18	$ 39.00	$ 3.00	$ 20.00	$ 24.00	$ 1.00	$ 87.00
21	Residential Med Density	n/a									

Site		Residential Cooling Effects								
Site	Type	Tree Savings	Savings per Home	Kw Hours Saved	KWH per Home	Carbon Gen Avoided	Carbe Gen Avoided/Home	Age Dist. Of Trees	Carbon Storage (tons)	Carbon Sequestration (lb/yr)
1	Residential Low Density	$ 311.73	$ 77.93	3848.49	962.1225	140301.23	35075.308	Mature	113	400
2	Residential Med Density	$ 148.01	$ 10.57	1827.3	130.52143	66616.35	4758.3107	Mature	50	180
3	Open Land	$ -		0	0	0	0	Mature	151	520
4	Recreational	$ -		0	0	0	0	Mature	66	120
5	Recreational	$ -	$ -	0	0	0	0	Mature	64	220
6	Commercial	$ -		0	0	0	0	Mature	22	80
7	Recreational	0		0	0	0	0	Mature	3	20
8	Residential Low Density	$ 31.67	$ 10.56	391.04	130.34667	14255.84	4751.9467	Mature	56	200
9	Residential Med Density									
10	Commercial	$ -		0	0	0	0	Young	25	1120
11	Commercial	$ -	$ -	0	0	0	0	Mature	2	0
12	Residential High Density	$ -		0	0	0	0	Mature	7	20
13	Residential Med Density									
14	Open Land	$ -		0	0	0	0	Mature	5	20
15	Open Land	$ -		0	0	0	0	Average	223	3480
16	Residential High Density	$ 211.26	$ 15.09	2608.16	186.29714	95083.48	6791.6771	Mature	44	160
17	Residential Low Density	$ 47.51	$ 11.88	586.56	146.64	21383.76	5345.94	Mature	8	20
18	Residential Med Density	$ 200.74	$ 9.56	2478.22	118.01048	90346.39	4302.209	Mature	48	160
19	Residential Med Density	$ 153.19	$ 9.57	1891.25	118.20313	68947.78	4309.2363	Mature	27	100
20	Residential High Density	$ 205.98	$ 11.44	2542.98	141.27667	92707.51	5150.4172	Mature	17	60
21	Residential Med Density									

APPENDIX E

Tree Canopy Rainfall Interception References

RAINFALL INTERCEPTION BY SACRAMENTO'S URBAN FOREST

by Qingfu Xiao[1], E. Gregory McPherson[2], James R. Simpson[2], and Susan L. Ustin[1]

Abstract. A one-dimensional mass and energy balance model was developed to simulate rainfall interception in Sacramento County, California. The model describes tree interception processes: gross precipitation, leaf drip, stem flow, and evaporation. Kriging was used to extend existing meteorological point data over the region. Regional land use/ land cover and tree canopy cover were parameterized with data obtained by remote sensing and ground sampling. Annual interception was 1.1% for the entire county and 11.1% of precipitation falling on the urban forest canopy. Summer interception at the urban forest canopy level was 36% for an urban forest stand dominated by large, broadleaf evergreens and conifers (leaf area index = 6.1) and 18% for a stand dominated by medium-sized conifers and broadleaf deciduous trees (leaf area index = 3.7). For 5 precipitation events with return frequencies ranging from 2 to 200 years, interception was greatest for small storms and least for large storms. Because small storms are responsible for most pollutant washout, urban forests are likely to produce greater benefits through water quality protection than through flood control.

Keywords. Urban forest; rainfall interception; numerical modeling; Kriging; geographic information system; remote sensing; urban runoff

Cities across the United States are focusing stormwater management efforts on control of nonpoint source pollution and flooding. Development in upstream portions of watersheds is increasing flooding hazard to established downstream communities. Urban stormwater runoff is the second most common source of water pollution for lakes and estuaries and the third most common source for rivers nationwide (EPA 1994). During normal rainfall, pollutants are washed from impervious surfaces, lawns, and other sources into streams and storm sewerage systems (Claytor and Schueler 1996). During heavy rainfall, excessive runoff can outstrip the storage capacity of storm sewerage systems and streams. Localized flooding is a frequent result, and pollutant loading can exceed desirable levels at receiving water bodies and treatment plants. Also, heavy runoff increases soil erosion, as well as the transport and downstream deposition of pollutant-laden sediment.

A healthy urban forest can mitigate stormwater impacts of urban development (Sanders 1986; Lormand 1988). Trees intercept and store rainfall on leaves and branch surfaces, thereby reducing runoff volumes and delaying the onset of peak flows. Root growth and decomposition increase the capacity and rate of soils to infiltrate rainfall and reduce overland flow. Urban forest canopy cover reduces soil erosion by diminishing the impact of raindrops on barren surfaces. This study focuses on interception of rainfall by Sacramento's urban forest. Our objectives are to 1) quantify annual rainfall interception, 2) describe relations between interception and rainfall seasonality, duration, and volume for typical storm events, and 3) identify important structural traits of urban forests that can be manipulated to increase rainfall interception.

Background

Several studies have simulated urban forest impacts on stormwater runoff. Dayton, Ohio's, existing tree canopy cover (22%) was found to lower potential runoff from a 6-hour, 1-year storm by about 7% (Sanders 1986). By increasing tree cover to 50% over all pervious surfaces, runoff reduction was increased to 12%. Five years of rainfall and runoff data were used to calibrate a simulation model for a small urban watershed in Tucson, Arizona. Increasing tree canopy cover from 21% (existing) to 35% and 50% was projected to reduce mean annual runoff by 2% and 4%, respectively (Lormand 1988). These findings and more recent results (American Forests 1996) suggest that urban forest management can have a modest influence on runoff volume.

The simulation results reported above relied on application of models derived from TR-55 (Soil Conservation Service 1975). The TR-55 model and its adaptations are widely used to evaluate effects of land use change on runoff. However, they are limited in their capabilities to accurately estimate effects of urban forest management on runoff volume and peak rate. Some important limitations include the following.

1. Empirically derived runoff curve numbers are assigned for specific land or land cover types. Variations in the species composition and structure of urban forests within and among land use/ land cover types are not incorporated in the curve numbers. Therefore, impacts of selecting and locating different types of trees in alternative configurations cannot be evaluated.
2. Curve numbers were originally developed from 24-hour storm data and are assumed to be constant for a large range of rainfall events. Thus,

TR-55 is better at predicting longer, larger storm events than smaller, shorter events (Pitt 1994). Because small storms are responsible for most annual urban runoff and pollutant washoff, accurate simulation of shorter events is important for water quality resource protection.

3. It is limited in computing the time of concentration and peak rates of flow for small catchments. This limits use of the model for flooding analysis.
4. Interception is held constant regardless of storm characteristics. Interception and depression storage (stormwater held in surface depressions) are modeled as storage capacities that are filled before overland flow begins. In fact, interception is a dynamic process, with canopy storage changing as water evaporates from the crown, drips from leaves, and flows down branches (Calder 1996).

Water quality is strongly related to water quantity or runoff. Canopy interception changes runoff quantity and the pollutant load from the canopy surfaces. Although hydrologic simulations using TR-55 and its adaptations have quantified effects of increasing and decreasing canopy cover on runoff, a better understanding of interception processes is needed to assist managers interested in managing urban forests for hydrologic benefits.

Forest canopy interception has been studied in both laboratory and field experiments (Rutter et al. 1971; Aston 1979; Gash et al. 1995). In rural forests, Zinke (1967) found that 15% to 40% of annual gross precipitation can be lost by interception in conifer-dominated forests and 10% to 20% in hardwood-dominated forests. Interception may exceed 59% for old growth forest trees (Baldwin 1938). However, information on interception by open-grown urban trees is lacking.

Statistical models estimate interception as a linear proportion of gross precipitation (Horton 1919; Zinke 1967). Regression coefficients for statistical methods are difficult to obtain because they are site specific and a long historical data record is needed to derive these coefficients. In contrast to the statistical approach, Rutter et al. (1975, 1977) developed a physically based canopy interception model that computes the water balance of canopy and trunk components. This approach was successfully tested (Gash and Morton 1978; Lloyd et al. 1988) with data from a coniferous plantation in Great Britain. Based on the assumption that the time lag between rainfall events was long enough for the canopy surface to dry, an analytical model was developed by Gash (1979) that has a simple form and is easier to apply than Rutter's model. Some other physically based interception models (Calder 1977; Gash et al. 1980; Massman 1983) have been developed and applied to natural forests and found to produce results in agreement with field observed interception.

Forest-derived interception models may not be applicable to urban forests because both the microclimate and tree architecture of urban forests are different from those of rural forests. The gradient of microclimate can vary more quickly in urban forests than in rural forests. Microclimate differences affect evaporation rates, leaf drip, and other hydrologic processes in the tree crown. Compared with most rural forests, urban forests have fewer trees per unit area, tree size (dbh, diameter at breast height) that is larger on average, a more diverse mix of species with different phenological patterns, and greater spatial variation in canopy cover (McPherson 1998). Gash et al. (1995) found that existing interception models need to be reformulated for sparse forests.

In this study, a one-dimensional numerical model of rainfall interception was developed based on the previous work of Rutter et al. (1971) and Gash (1979). Rutter and Gash's model is physically based, and their parameters are easy to obtain. We used drying power of the air to estimate potential evaporation (Pruitt and Doorenbos 1977a, 1977b). Remotely sensed data and GIS techniques were used to characterize the land surface and link the model to specific local conditions.

Study site. Sacramento County is located in the lower Sacramento Valley of California and falls within the coordinates between longitudes W121°51'43" and W121°01'20". For a more complete description of the study area and sampling units, see McPherson 1998 (pages 175–177 of this issue).

Methodology

The interception model. Gross precipitation is either intercepted by canopy leaves, branches, and trunk, or it falls directly to the ground without hitting the tree. Intercepted water is stored temporarily on canopy leaf and bark surfaces, eventually drips from leaf surfaces, and flows down tree stem surfaces to the ground, or it evaporates. Interception accounts for the sum of canopy surface water storage and evaporation. Interception loss accounts for the evaporation of water from canopy surfaces during the rainfall event and the evaporation of retained water on canopy surfaces after both canopy drip and stem flow cease. The total water balance on a canopy surface can be expressed by the following equation:

$$Interception = C + E = P - TH - F - D \qquad (1)$$

where C is the canopy surface water storage (mm), which includes water storage on leaf and trunk surfaces); E is evaporation from canopy surfaces (mm), which includes evaporation from leaf, branches and trunk surfaces; P is gross precipitation (mm); TH is free throughfall (mm) (precipitation directly passing through the canopy); F is stem flow (mm); and D is water drip from leaves and branches (mm). For this interception model, gross precipitation P was directly measured and the remaining variables were calculated from tree and climatic data. A detailed description and derivation of this model are presented in the appendix.

Model parameterization and scale up. We assumed that total rainfall interception is the summation of interception for all trees. Further, we assumed that leaf surface temperature is in equilibrium with air temperature and that leaf surface area is constant throughout the leaf-on (mid-March to mid-November) and leaf-off periods. At the smallest scale, interception was calculated for each cell in a grid system of length dx (100 m [330 ft]) and dy (100 m) that was superimposed on the study area. Interception was analyzed at 2 spatial scales: SubRADs (Sub-Regional Assessment Districts) and sectors. Interception values were aggregated for each of the 71 SubRADs and for each of the 3 sectors. Three groups of parameters were estimated.

Tree canopy characterization. Aerial photos and ground surveys were used to estimate tree species composition, tree dimensions, crown projection area (area enclosed by the dripline), and leaf surface area by SubRAD (see McPherson 1998, beginning on page 175 of this issue, for a detailed explanation of methods). Vegetation was divided into 3 categories: tree, shrub, and grass. Trees were further divided into broadleaf evergreen, broadleaf deciduous, conifer, and palm. Tree canopy parameters included species, leaf area (McPherson 1998), shade coefficient (visual density of the crown from McPherson 1984), and tree height. Three tree height classes were established: large (> 15 m [50 ft]), intermediate (5 to 15 m [16.5 to 50 ft.]), and small (< 5 m). Tree height data were used to estimate wind speed at different heights above the ground and the resulting rates of evaporation (Jetten 1996). The volume of water stored in the tree crown was calculated from crown projection area (area under tree dripline), leaf area indexes (LAI, the ratio of leaf surface area to crown projection area), and water depth on the canopy surface. Species-specific shade coefficients influenced the amount of projected throughfall. Although rainfall is intercepted by trees, shrubs, and buildings, in this study we focused on rainfall interception by trees only.

Precipitation and potential evaporation. Scaling-up meteorological data from a limited number of stations to a region has been widely applied in hydrological and climatic studies (Hungerford et al. 1989; Ustin et al. 1996; Xiao 1997). A Kriging method (Edward and Srivastava 1989) was used to extrapolate precipitation and evaporation data from a meteorological base station to the entire study area. Precipitation and evaporation coefficients of each grid cell were estimated as the ratio of the value at the cell to the value at the base station based on the spatial data extrapolation results from Kriging. The Stonemead base station (38°30′31″ N, 121°17′36″ W, elevation 37 m [122 ft]) is located near the center of the study area and has been operated since 1982 by the California Department of Water Resources.

Meteorological parameters were derived based on data obtained from NOAA (National Oceanic and Atmospheric Administration), CIMIS (California Irrigation Management Information System), and CDEC (California Data Exchange Center) meteorological stations located in or near the study area. Mean precipitation (from 57 stations) and evaporation (40 stations) data from stations with more than 20 years of meteorological records were used to create long-term averages for their respective grid cells. These data, in conjunction with Kriging, allowed us to conduct simulations for a variety of time intervals and weather conditions.

Numerical simulation. This study focused on the spatial and temporal distribution of canopy interception in Sacramento County. Three sets of simulations were conducted.

Annual interception. Data for a typical meteorological year (determined to be 1992 based on analysis of 10 years meteorological data at Stonemead station) were used to simulate annual canopy rainfall interception over the entire study area. Among the total 30 storms in 1992 at Stonemead, 7 storms had precipitation greater than 25.4 mm (1 in.), and these events accounted for 77% of total annual precipitation. Seven storms had precipitation between 6.2 and 25.4 mm (0.25 to 1 in.), accounting for 17% of total annual precipitation. The remaining 16 events were each less than 6.2 mm and accounted for 6% of annual precipitation. We assumed that individual storms were separated by intervals of at least 24 hours without precipitation (Hamilton and Rowe 1949).

Summer and winter storm events. We simulated rainfall events occurring during summer (May 31, 1993) and winter (December 3, 1994) to examine effects of tree species composition and size on interception. The summer event depicted interception when deciduous trees were in-leaf, while the winter event occurred during the leaf-off season. Our analysis was limited to 2 adjacent SubRADs in the northern part of the county with very different forest structures. The rural SubRAD (Rio Linda–Elverta, 12.3 km^2 [4.7 mi^2]) was dominated by relict native oaks and conifers (68% of the trees were broadleaf evergreen and 17% coniferous). The city SubRAD (North Sacramento, 15.7 km^2 [6 mi^2]) contained a diverse mix of introduced shade trees and conifers characteristic of established neighborhoods near downtown Sacramento (50% of the trees were broadleaf deciduous and 41% coniferous).

Flood events. Five additional storm events were selected to study interception for rainfall of different amounts and durations. Using the same two SubRADs as described above, we simulated precipitation events with return frequencies of 2, 5, 25, 100, and 200 years to better understand the extent to which Sacramento's urban forest can mitigate flooding. Rainfall events were selected from Stonemead's 1990 to 1997 records based on depth-duration-frequency relationships developed by the local flood control agency (City/County of Sacramento 1996). We simulated interception assuming both leaf-on and leaf-off conditions for deciduous trees for both the rural and city SubRAD sites.

Simulation results (annual, seasonal, and flood events) are presented at the urban forest canopy level and landscape level. Interception at the urban forest canopy level is the percentage of total precipitation falling on the urban forest canopy that is intercepted by the canopy (mm^3 interception per mm gross precipitation per mm^2 crown projection area). Interception at the landscape level is the percentage of total precipitation falling on the entire study site that is intercepted by the urban forest canopy (mm^3 interception per mm gross precipitation per mm^2 total land area).

To reduce numerical estimation errors, interception processes were simulated with an hourly time-step for analysis of annual interception and a 1-minute time-step for seasonal and flooding events. Due to the relatively small amount of stem surface area compared to leaf surface area (Vertessy et al. 1995) and low evaporation rate (Rutter and Morton 1977; Gash 1979), evaporation from stem surfaces was ignored by forcing the stem surface water storage capacity to zero.

Results

Annual interception. Annual rainfall interception by the tree canopy for the county averaged 1% at the landscape level and 11% at the urban forest canopy level for the 1992 meteorological year (Tables 1 and 2). At the landscape level, interception was greatest in the suburban sector, where leaf area index and canopy cover were greatest (Figure 1). Interception was least

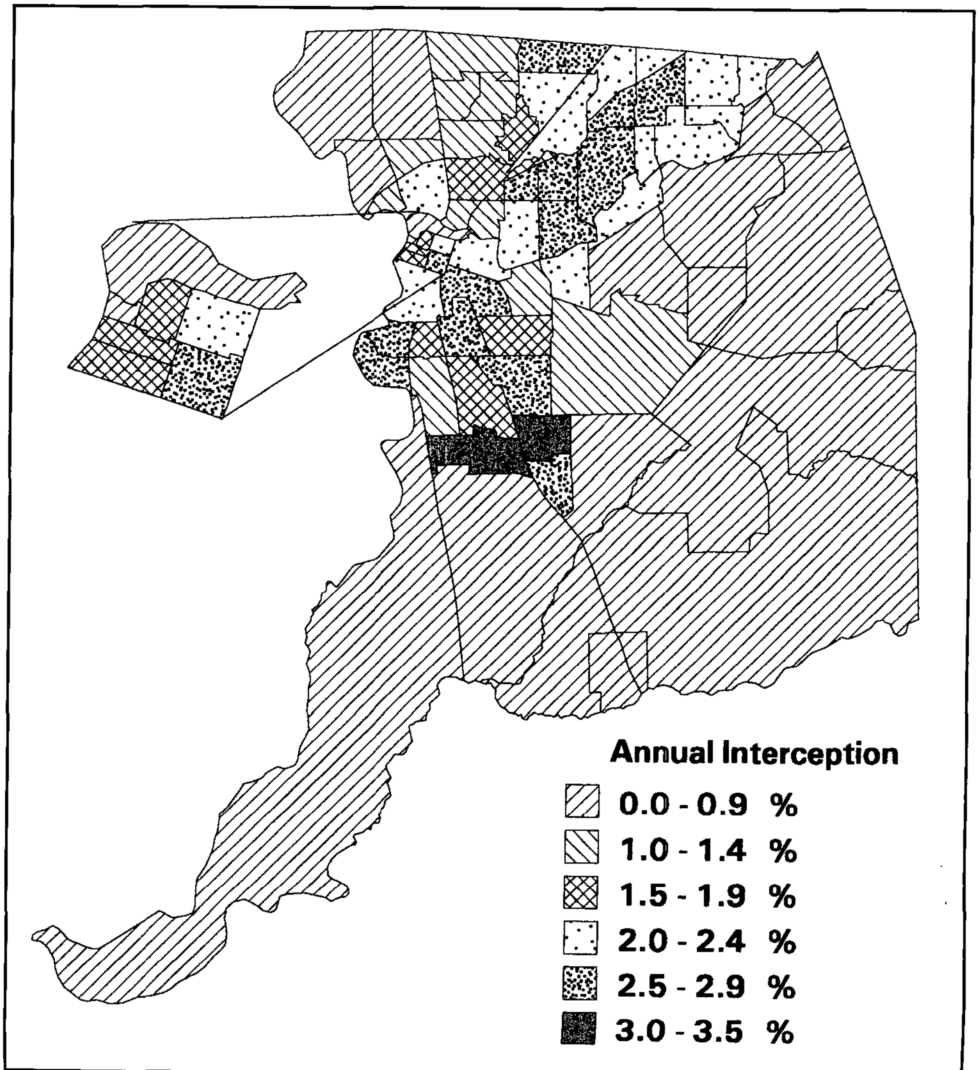


Figure 1. Spatial distribution of annual interception at landscape level; see equation 1.

Table 1. Leaf area and canopy cover distribution.

			Leaf area (km²)			
Sector	Area (km²)	Canopy	BE[a]	BD[b]	Conifer	Palm
City	236.0	13.0%	15.7	126.2	118.5	8.4
Suburban	371.4	15.4%	239.4	182.7	182.9	7.9
Rural	1,970.9	5.2%	358.3	92.5	92.8	0.0
County	2,578.3	7.4%	613.4	401.4	394.2	16.3

[a]Broadleaf evergreen.
[b]Broadleaf deciduous.

Table 2a. Annual rainfall interception at the urban forest canopy level (mm), Sacramento County.

Sector	Gross precipitation	Interception	Free throughfall	Leaf drip	Stem flow
City	393.2	23.5	266.3	101.0	2.5
Suburban	433.2	56.3	186.5	238.0	2.7
Rural	415.5	55.4	121.2	236.3	2.6
County	414.1	45.9	186.3	179.3	2.6

Table 2b. Annual rainfall interception by percentage, Sacramento County.

Sector	Landscape level	Urban forest canopy level
City	1.8	6.0
Suburban	2.6	13.0
Rural	0.6	13.3
County	1.0	11.1

in the rural sector due to its relatively low tree density, basal area, and canopy cover.

At the urban forest canopy level, interception was strongly influenced by the mix of tree species and their phenology. Interception was lowest in the city sector, where broadleaf deciduous trees dominated and were leafless during the winter rainy season (Table 1). In the suburban sector, broadleaf evergreens and conifer trees accounted for 67% of total leaf area. In addition to maintaining foliage year-round, evergreens generally have higher LAIs than deciduous trees, thereby increasing canopy storage per unit crown projection area. Annual interception was as high as 22% for suburban SubRADs.

Summer and winter storm events. From the outset of the 6-hour, 12 mm (0.48 in.) summer storm (May 31, 1993), canopy storage increased until saturated after about 2 hours in the city SubRAD and about 2.5 hours in the rural SubRAD (4 mm [0.16 in.]) (Figure 2). Maximum canopy storage in the rural SubRAD was nearly twice that of the city SubRAD (4.5 and 2.3 mm [0.18 and 0.09 in.). For the next 2 hours of relatively heavy rainfall, most precipitation reached the ground as leaf drip, throughfall, and stem flow. From hours 4 to 6, the rainfall rate decreased and canopy storage gradually increased. After a continuously high leaf drip rate during hours 3 to 3.5 in the rural SubRAD, and

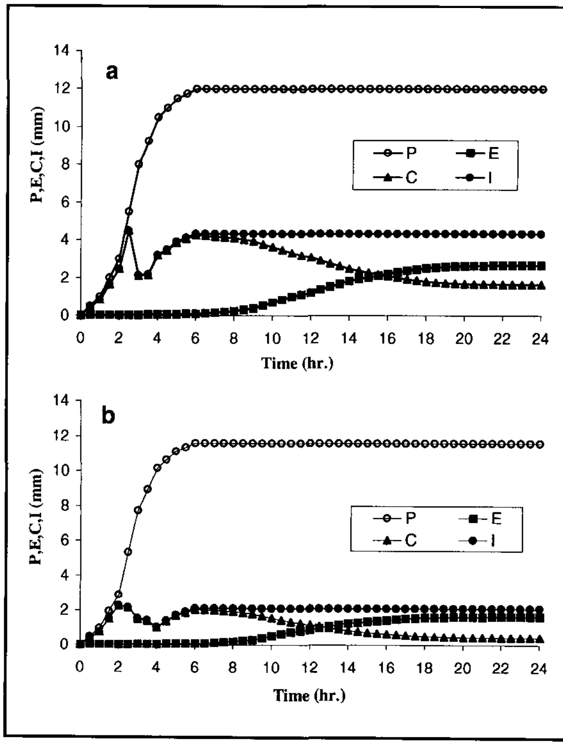


Figure 2. Distribution of rainfall interception in a rural SubRAD (a) and city SubRAD (b) during a summer storm (May 31, 1993). P is gross precipitation, E is evaporation, C is canopy storage, and I is canopy rainfall interception. P, E, C, and I have units in mm of water.

hours 3.5 to 4 in the city SubRAD, canopy water storage was less than the maximum storage capacity. The small amount of rainfall added was not enough to fill canopy water storage to capacity. Once the rainfall stopped, canopy storage dropped and evaporation of intercepted rainfall began.

At the urban forest canopy level for the summer storm, interception loss was 36% and 18% for the rural and city SubRADs, respectively (Figure 2). Taller trees and more tree species with relatively high LAIs in the rural than city SubRAD resulted in higher canopy storage and evaporation rates. More than 55% of trees in the rural SubRAD were large (tree height > 15 m [50 ft]) and the LAI was 6.1, while more than 58% of the trees in the city SubRAD were medium size (height between 10 and 15 m [33 and 50 ft.]) with LAIs of 3.7 (Table 3).

The winter storm event (December 3, 1994) was much longer (44 hours) and larger (45 mm [1.78 in.]) than the summer event (Figure 3). Canopy storage steadily increased for about 6 hours, then declined once water began to drip off leaves and stems of

Table 3. Leaf area distribution by tree type and height class (leaf-on season).

Tree type/height class	Leaf area (% of total SubRAD) Rural SubRAD	City SubRAD
Broadleaf deciduous		
Large[a]	5.7%	27.2%
Medium[b]	9.5%	21.4%
Small[c]	0.0%	1.4%
Subtotal	**15.2%**	**50.0%**
Broadleaf evergreen		
Large	39.0%	0.9%
Medium	29.1%	2.0%
Small	0.1%	1.7%
Subtotal	**68.2%**	**4.6%**
Conifer		
Large	10.3%	7.4%
Medium	4.5%	34.3%
Small	1.8%	0.4%
Subtotal	**16.6%**	**42.1%**
Palm		
Large	0%	1.7%
Medium	0%	1.5%
Small	0%	0.1%
Subtotal	**0%**	**3.3%**
Average LAI	6.1	3.7

[a]Tree height greater than 15 m [50 ft].
[b]Tree height 5 to 15 m [16.5 to 50 ft].
[c]Tree height less than 5 m [16.5 ft].

saturated canopies. This pattern was repeated throughout the storm event as the canopy intercepted and lost rainfall in response to precipitation, leaf drip, and evaporation. It should be noted that evaporation rates were relatively low during the winter event. Compared to the summer event, air temperatures were cooler, relative humidity was higher, and net radiation was lower. Lower evaporation rates and lower LAI due to trees in a leaf-off condition (hence less canopy storage capacity) were primarily responsible for 14% (rural) to 26% (city) less interception during the winter event than the summer event.

At the urban forest canopy level, interception was 10% and 4%, respectively, in the rural and city SubRADs. Broadleaf deciduous trees were leafless in December, which reduced LAIs to 5.2 and 1.8, respectively, for the rural and city SubRADs. During winter, condensation sometimes occurs on plant surfaces from dew and fog. Higher LAIs and more evergreen trees in the rural compared to city SubRAD account for increased fog trapping and interception.

Total canopy interception for the winter event in rural and city SubRADs was 4,212 m^3 (3.41 acf) and 6,103 m^3 (4.95 acf), respectively. This volume of water would increase detention storage of a 1 km^2 (247 ac) basin by a depth of 19 mm (0.75 in). Because tree crowns provide a type of detention storage, these results could be used as the basis for determining the economic value of canopy surface water storage.

Flood events. Canopy interception for 5 flooding events was greater for smaller, shorter storms than for larger and longer storm events (Table 4). During small events, a relatively large percentage of gross precipitation was required to fill canopy storage to capacity. Once storage was filled, relatively little precipitation was needed to maintain canopy saturation. Therefore, canopy interception had a minor impact on major flood events. For example, during the 200-year storm event, leaf-on interception loss was only 9% for the rural SubRAD and 5% for the city SubRAD (Table 4). In contrast, leaf-on interception was 37% and 20% for the 2-year event in the Rural and City SubRADs, respectively.

Differences between canopy interception for the leaf-on and leaf-off events reflected the impact of broadleaf evergreens and conifers in each SubRAD. Greatest interception loss occurred during the leaf-on season in both SubRADs. However, differences between leaf-off and leaf-on interception were greatest

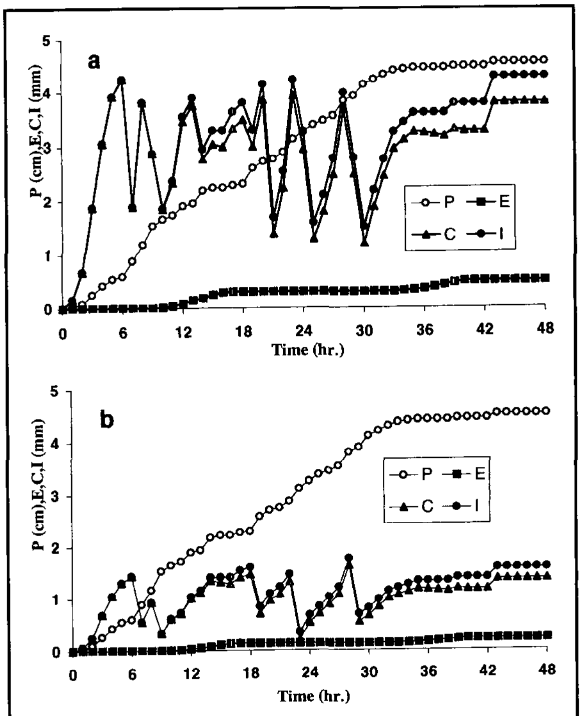


Figure 3. Temporal distribution of rainfall interception processes in a rural SubRAD (a) and city SubRAD (b) during a winter storm (December 3, 1994). P is gross precipitation, E is evaporation, C is canopy storage, and I is canopy rainfall interception.

Table 4. Rainfall interception at the urban forest canopy level.

Flood analysis events[a]			Actual precipitation		Interception (%)			
					Rural SubRAD		City SubRAD	
Year	Amount/duration (mm [hours])	Date	P[b] (mm)	Duration (hours)	Leaf-off	Leaf-on	Leaf-off	Leaf-on
200	51.6 [3]	Jan. 9, 1995	64	5	7.4%	8.7%	2.4%	4.9%
100	40.4 [2]	Apr. 3, 1996[c]	49	6	9.1%	9.7%	3.8%	7.4%
25	32.0 [2]	Jan. 10, 1995[d]	32	3	9.6%	11.0%	5.7%	8.9%
5	22.4 [2]	Feb. 28, 1991	24	4	15.3%	17.9%	6.4%	10.7%
2	11.4 [1]	Feb. 18, 1996	15	2	32.8%	36.9%	9.9%	19.7%

[a]From *Sacramento County Drainage Manual 1997.*
[b]Precipitation at base station.
[c]Storm occurs during leaf-on time.
[d]97% rainfall in first 2 hours.

in the city, where leaf-on loss was about 70% to 100% greater than leaf-off loss due to the relative abundance of broadleaf deciduous trees (Table 3). The large evergreen component in the rural SubRAD accounted for a smaller seasonal difference of about 20%. As previously noted, greater overall leaf area in the rural versus city SubRAD was responsible for higher interception loss for all storm events.

Limitations of the model. This canopy interception model allows water to drip from leaves only after canopy storage exceeds saturated canopy storage. Because some leaf drip begins before canopy saturation, the model overestimates actual interception. During winter rainfall, water stored on stem surfaces is a large proportion of rainfall interception and temporary canopy water storage. By ignoring stem surface water storage, the model underestimates interception, especially for urban forest stands dominated by deciduous trees. In this study, only rainfall interception by trees is modeled. Shrubs and grasses also contribute to total interception. A full water budget includes contributions from all vegetation layers. This model has not been calibrated or validated with measured data from individual trees or an urban watershed. Thus, findings are approximations.

Discussion and Conclusion

Annual interception by the region's urban forest was 11.1% at the urban forest canopy level, close to reported values for hardwood forest stands. However, because of the region's relatively low tree density and the pattern of winter rainfall when deciduous trees are leafless, interception was only 1.1% at the county landscape level. At the landscape level, canopy interception reflected such structural attributes as tree density, basal area, and canopy cover. Increasing overall tree canopy cover will result in a direct increase in canopy interception.

At the urban forest canopy level, the mix of tree species and their size structures influenced interception. In Sacramento, evergreen trees played the most important role in interception because most precipitation occurs in winter. Large trees with evergreen foliage contribute to greater interception than smaller, deciduous trees. In many climates with summer precipitation, deciduous trees make a substantial contribution to rainfall interception. Planting trees, as well as maintaining existing trees in a healthy condition, will reduce the volume of stormwater runoff over the long term.

These results indicate that urban forests become increasingly less effective at reducing stormwater runoff as the amount of precipitation per storm increases. Although trees reduce runoff, they may not be very effective for flood control. Floods usually occur during major storm events, well after canopy storage has been exceeded. However, by substantially reducing the amount of runoff during less extreme events, urban forests may protect water quality. Small storms, for which urban forest interception is greatest, are responsible for most annual pollutant washoff. Infrequently occurring large storms usually produce greatest flooding damage, and although they may contain significant pollutant loads, their contribution to the annual average pollutant load is quite small (Chang et al. 1990). Also, because of the infrequent occurrence of large storms, receiving waters have relatively long periods of recovery between events (Claytor and Schueler 1996). Therefore, urban forests are likely to produce more benefits through water quality protection than through flood control. Research is needed to better understand the interception process for open-grown urban trees, as well as the impacts of canopy interception on water quality.

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Appendix: The Interception Model

Precipitation water balance on a canopy surface can be expressed as:

$$C = P - TH - F - D - E \quad \text{(A1)}$$

where *P* is gross precipitation (above canopy), and *TH* is free throughfall, which is the portion of precipitation that directly falls on the ground surface without hitting the canopy surface. *F* and *D* are stem flow and the water drip from canopy surface, and *E* is evaporation from the canopy surface.

Differentiating equation (A1) with time gives the general canopy interception equation:

$$\frac{dC}{dt} = p - th - f - d - e \quad \text{(A2)}$$

where *p, th, f, d,* and *e* are the rate (mm/sec) of precipitation, throughfall, stem flow, canopy drip, and evaporation; *t* is time (sec).

Interception (*I*) is the sum of canopy surface water storage (*C*) and evaporation (*E*). Interception loss (L_i) accounts for all of the water evaporated from canopy leaf and branch surface (*E*).

Canopy drip rate is described as an exponential function of canopy storage and saturation storage capacity (Rutter et al. 1971; Lloyd et al. 1988; Jetten 1996):

$$d = 0 \qquad C < S$$
$$d = d_0 e^{b(C-S)} \qquad C \geq S \quad \text{(A3)}$$

where *S* is the canopy surface saturation storage capacity (mm), d_0 is the minimum drainage rate (mm/sec), which is the drainage rate when *C* equals *S*, and *b* is a dimensionless parameter.

To calculate drainage from stem surfaces (stem flow), we assume that water available on stem surfaces for drainage is supplied mainly by the proportion of the gross precipitation ($p_s p$) and lost by both flow and evaporation. Evaporation from stem surface storage is small compared with evaporation from leaf surfaces. Rutter and Morton (1977) estimated it as 1% to 5% of the canopy evaporation value. Stem flow is calculated as directly proportional to precipitation ($q_{stem} = p_s p$). Free throughfall is calculated as a fraction of gross precipitation ($th = p_t p$), where p_t is the canopy shading coefficient.

Canopy evaporation is described as (Rutter et al. 1971):

$$e = E_p \qquad C \geq S$$
$$e = E_p \frac{C}{S} \qquad C < S \quad \text{(A4)}$$

where E_p is potential evaporation rate (mm/sec) estimated using the Penman formula (Penman 1948):

$$E_p = \frac{\Delta}{\Delta + \gamma} Q_{ne} + \frac{\gamma}{\Delta + \gamma} E_A \quad \text{(A5)}$$

where Δ is the rate of increase with temperature of the saturated water vapor pressure at air temperature, γ is the psychometric constant (Pa/K). Net radiation Q_{ne} (mm/sec) and drying power of the air E_A (mm/sec) are defined as:

$$Q_{ne} = c_1 \frac{R_n}{L_e} \quad \text{(A6)}$$

$$E_A = c_2 f_e(u_r)(e_a^* - e_a) \quad \text{(A7)}$$

where R_n is net radiation (W/m²), L_e is latent heat of vaporization of water (J/kg), e_a* and e_a are saturation vapor pressure and vapor pressure at air temperature (Pa), c_1 and c_2 are unit constants used to convert between W/m² and mm. $f_e(u_r)$ is the wind function described as (Pruitt et al. 1977a, 1977b):

$$f_e(u_r) = a_u + b_u u(z) \quad \text{(A8)}$$

where a_u and b_u are constants, and *u*(*z*) is wind speed measured at height *z* (m/sec).

In equation (A5), we use drying power of the air instead of aerodynamic resistance to calculate potential evaporation because the wind function (equation A8) is well studied in the study area (Pruitt et al. 1977a, 1977b). Simulation accuracy should increase due to the way evaporation is estimated.

Net radiation is calculated from solar radiation (Monteith 1973; Roland 1988; Dong et al. 1992). The wind profile at the meteorological station was retrieved from the wind speed measured at stand height (2 m [6.6 ft.] from ground surface) (Brutsaert 1988; Jetten 1996). We are not extrapolating air temperature and relative humidity from measurement height to actual canopy height because the vertical gradient is small.

Boundary and initial conditions must be determined before we can start solving these equations. Two flux boundaries are defined: upper boundary (at the canopy top) is determined by precipitation and evaporation rates, and lower boundary (at ground surface) is determined by canopy drainage (throughfall) and stem flow rates. To determine initial conditions, we assume that the canopy surface is dry before initiation of the precipitation event.

The model (equation A1) is explicitly solved using finite differences. Numerical instability errors are reduced by limiting the maximum time step. Assuming air temperature and relative humidity measured from meteorological stations are representative of the canopy surface, these data can be used directly without modification.

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[1]*Hydrologic Sciences, Dept. of Land, Air, and Water Resources*
University of California
Davis, CA 95616

[2]*Pacific Southwest Research Station*
USDA Forest Service
c/o Department of Environmental Horticulture
University of California
Davis, CA 95616

Résumé. L'interception de la pluie par la forêt urbaine a été étudiée dans le comté de Sacramento en Californie, une région où l'urbanisation est importante. En se basant sur la masse et sur la balance énergétique, un modèle similaire à celui de Rutter (1977) a été utilisé pour simuler l'interception de la pluie. Le modèle décrit les processus d'interception par les arbres à partir de données sur les quantités bruts et nets de précipitation, le ruissellement des feuilles, l'écoulement le long des tiges et l'évaporation. La méthodologie pour appliquer ce modèle unidimensionnel à un écosystème régional urbain est discutée. Une méthode particulière a été employée pour élargir à toute la région les données météorologiques recueillies à partir d'un point de mesure. Des techniques faisant appel aux systèmes d'information géographique (GIS) et à d'anciennes données de mesure ont été utilisées pour caractériser les utilisations locales du territoire et leur superficie. L'application de ce modèle à la forêt urbaine de Sacramento a permis de montrer que les pertes de précipitation par interception varient énormément selon la saison et la localisation. Au niveau du sol, la perte annuelle de précipitations suite à l'interception au niveau du couvert arboré a été évaluée à 1% dans la zone rurale et à 4% dans la zone urbaine. Au niveau de la cime des arbres, sous leur projection, les pertes annuelles suite à l'interception varient de 14% en zone urbaine à 17% en zone rurale. Lors d'une averse estivale – au niveau de la cime des arbres, sous leur projection – 42% des pertes en précipitations bruts sont dues à l'interception par le couvert arboré.

Zusammenfassung. Im Regierungsbezirk von Sacramento, CA, einer Region mit extensiver Besiedelung, wurde die Aufnahme von Niederschlägen durch einen urbanen Forst studiert. Basierend auf einer Massen- und Energiebilanz wurde ähnliches Modell wie Rutter (1977) genutzt, um die Niederschlagsaufnahme durch den Baum unter den Blattropfen, Stammabfluß und der Evaporation. Hier wird der methodische Ansatz für die Anwendung eines eindimensionalen Modells auf ein regionales, urbanes Ökosystem diskutiert. Die existierenden metereologischen Einzeldaten wurden auf die Region ausgedehnt. Um die Landnutzung und die Vegetationsdecke zu charakterisieren, wurde GIS (Geographisches Informationssystem) genutzt. Die Übertragung von diesem Modell auf die urbanen Forste von Sacramento zeigt, daß Verluste der aufgenommen Niederschläge stark swischen der Jahreszeit und der Örtlichkeit variieren. Im Bereich der Landschaft detrug der jährliche Niederschlagsverlust wegen der Aufnahme durch das Laubdach 1 % in der Stadt und 4 % auf dem Land. Auf der Projektionsebene der Baumkrone varooerte der jähjrliche Aufnahmeverlust zwischen 14 % in der Stadt und 17 % auf dem Land. Während eines Sommeregens gingen 42 % des Bruttoniederschlages infolge der Aufnahme durch die Baumkronen (auf dieser Projectionsebene) verloren.

Resumen. Se estudió la intercepción de la lluvia por un bosque urbano en el Condado de Sacramento, California, una región de urbanización extensiva. Se utilizó un modelo similar al de Rutter (1977), basado en balance de energía y masa, para simular la intercepció n de la lluvia. El modelo describe los procesos de intercepció n de los árboles en aspectos de precipitació n total, precipitació n neta, goteo foliar, escurrimiento por el tronco y evaporació n. Se discute la metodología para aplicar este modelo unidimensional a un ecosistema urbano regional. Se usó Kriging para extender los datos meteorológicos puntuales a toda la región. Se utilizaron datos de sensorización remota y técnicas del Sistema de Información Geográfica (GIS) para caracterizar el uso regional de la tierra y la cobertura del terreno. La aplicación de este modelo al bosque urbano de Sacramento enseña que las pérdidas de intercepción de la lluvia varían fuertemente con la estación y la localidad. A nivel del paisaje la pérdida anual de precipitación debida a la intercepción foliar fue 1% en el sector Rural y 4% en el sector Ciudad. A nivel de la proyección de la copa de los árboles, las pérdidas anuales por intercepción variaron de 14% en el sector Ciudad a 17% en sector Rural. En un evento de lluvia de verano, 42% (a nivel de proyección de la copa) de la precipitación total se perdió debido a la intercepción de la copa.

Texas A&M Agricultural Research & Extension Center at Uvalde

Evaporation and Interception Water Loss from Juniper Communities on the Edwards Aquifer Recharge Area

M.K. Owens and R.K. Lyons

Bottom Line

- All of the rainfall in storms of <0.25 inches were intercepted by juniper canopies and evaporated into the atmosphere. On an annual basis, juniper trees can intercept almost one half of natural rainfall.

Introduction

Juniper trees can exert both a physiological and physical impact on local water budgets. Canopies can potentially intercept a significant amount of annual rainfall. Some of this intercepted water is transported via stemflow directly to the base of the tree, some is intercepted by the litter layer, and some is lost to the atmosphere through evaporation. All of these water losses can be attributed to the physical presence of a juniper tree and will decrease the amount of water available for either aquifer recharge or for other plants. This study was directed at determining the impact of juniper trees in areas of 24 to 34 inches of annual rainfall. The Texas Agricultural Experiment Station and the Texas Agricultural Extension Service, in cooperation with San Antonio Water Systems, Upper Guadalupe River Authority, San Antonio River Authority, Lower Colorado River Authority, and the Texas State Soil and Water Conservation Board developed a project to determine the amount of rainfall intercepted by individual juniper trees on the eastern portion of the Edwards Aquifer Recharge Area.

Experimental Approach

The project was conducted at ten locations in seven counties (Bexar, Blanco, Comal, Hays, Kendall, Kerr, Medina, and Uvalde) which stretch across the Edwards Aquifer Recharge and Drainage area. County Extension Agents in all of these counties were instrumental in locating and establishing these plots. Data for individual storms as well as year-to-date information may be viewed on the internet at **http://uvalde.tamu.edu/intercept**. Each site was equipped with an electronic datalogger to record data on a continuous basis. A tipping bucket rain gauge measured ambient precipitation at each site. In addition, two juniper trees at each site were instrumented as follows: A series of 4 collecting raingauges were placed under each tree and a system of tubing conducted the rain from these collection gauges to a storage container instrumented with a float and potentiometer to measure the amount of water which passes through the canopy (throughfall). Water intercepted by the canopy and transferred to the ground through stemflow was estimated by capturing all stem flow to a second tipping bucket gauge designed at the Uvalde Center. After the rainfall stopped (determined by the datalogger) a microswitch drained each of the storage containers so they were available for the next rainfall event.

Water loss to the litter layer was determined using moisture probes inserted into the litter. Calibration curves relating percent litter moisture to water content were developed for each site.

Rainfall was then partitioned and water loss was attributed to various physical attributes of juniper trees. Rainfall was first partitioned as either intercepted by the canopy or as throughfall. Throughfall was then further subdivided into either intercepted by the litter layer, or as available for runoff or soil infiltration. Rainfall intercepted by the canopy was divided into either evaporative losses or as stemflow. The stemflow water was also subdivided into either litter interception or as available for runoff or soil infiltration. The computer algorithm used to calculate these values is available upon request.

Water loss was calculated on a per storm basis and on an annual basis. In order to make the values comparable across the different sites, we converted rainfall (measured in hundreths of an inch) to gallons based on the tree sizes at each site. We then further calculated the partitioning based on a percentage of the rainfall received.

Results and Discussion

The first research site was installed on the Annandale Ranch in Uvalde County on August 7, 2000 and the last site was installed on December 19, 2000 in the western portion of Medina County. During the observation period, the site in Hays County at the Freeman Ranch received the most precipitation with over 36 inches of rain while the site at Kendall County received just 10.12 inches. This reflects the heavy rains received over the area in October and November before the Kendall County site was installed. The amount of rain received and rainfall partitioning for each site are presented in Table 1. Three sites (Hays, Kerr and West Bexar) had similar, low values for the amount of rainfall available for recharge or plant growth. These low values resulted from malfunctions of the equipment early in the study and modifications were subsequently made to the sampling system. At the other sites, approximately 57% of the rainfall received was available for either infiltration, recharge, or plant growth. Forty-three percent of the total rainfall was intercepted by the juniper canopy and evaporated to the atmosphere before it had a chance to reach ground level.

The relationship between rainfall amount and the percent of the rainfall intercepted was similar for all 10 sites (Figure 1, only 1 site shown). The first graph depicts the amount of rain in each rainfall and the percentage of that rain which was intercepted by the juniper canopy. The second graph depicts the frequency histogram of rain for that research site. For instance, at the Annandale Ranch (data shown) we received 89 rainfall events, ranging from 0.01 to 1.73 inches. Of those 89 rainfall events, 65 were < 0.25 inches and 78 were <0.5 inches. The regression lines represent the best-fit regression for the Annandale site, and the horizontal line represents 50% canopy interception. The exact shape of the relationship was different for each of the sites, but generally the light rainfall events of less than 0.25 inches had most of the rainfall intercepted by the juniper canopies. At all sites, the vast majority of rain events were <0.25 inches.

Table 1. Average rainfall partitioning within juniper canopies at the 10 study sites of the Edwards Aquifer.

	41.55	
Rain (in)	Gallons	Percent
Rain	5858.2	100
Canopy Interception	2488.0	
Stemflow	144.24	
Litter	337.65	5.7
Evaporation	2343.76	40.0
Available Water	3176.72	54.3

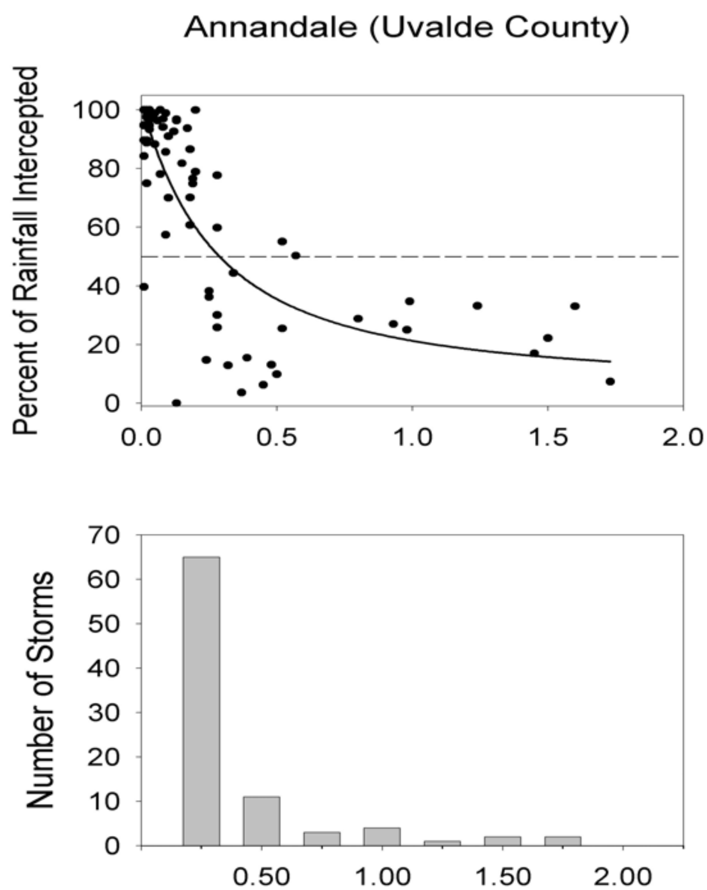

Figure 1. Rainfall interception and storm distribution on the Annandale Ranch from August 2000 through June 2001.

Urban Forest Research

July 2002

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Is all your rain going down the drain?

Trees are a solution

Have you ever gone outside after a rainstorm and looked around thinking… “where does all this rainwater end up?” Perhaps you can see some running down your driveway into the street. Or you have a large puddle forming on your front lawn. And then there is that flooded intersection at the end of your block because the storm drain is clogged. Sound familiar?

Communities throughout the U.S. are faced with this problem—too much water and not enough places to put it, so much of it is going “down the drain.”

You’ve probably heard it called another name—stormwater runoff. And its not surprising that stormwater runoff from urban, industrial, and agricultural sources is an environmental nemesis that EPA and other regulators have been trying to control for more than a decade. The agency claims that stormwater runoff is a leading cause of impairment to nearly 40% of U.S. waterways and led to more than 1,500 beach closings and advisories at coastal and Great Lakes sites in 1998.


Steve Lennartz

Urban Hydrology

As we build our communities, considerable natural landscape is converted to impervious surfaces such as roads, parking lots, driveways and buildings. Manmade drainage systems such as sewers and storm drains are used to improve water movement through communities

(continued next page)

Our website has been redesigned! Check it out at http://cufr.ucdavis.edu/

Center for Urban Forest Research
Pacific Southwest Research Station, USDA Forest Service
c/o Department of Environmental Horticulture
University of California
1 Shields Avenue, Suite 1103
Davis, CA 95616-8587

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How Benefits are Calculated

Our interception model accounts for water intercepted by the tree as well as throughfall and stem flow. Intercepted water is stored temporarily on canopy leaf and bark surfaces. Once the leaf is saturated, it drips from the leaf surface and flows down the stem surface to the ground or evaporates.

The volume of water stored in the tree crown was calculated from the crown projection area (area under tree dripline), leaf area indices (LAI, the ratio of leaf surface area to crown projection area), and water depth on the canopy surface. Species-specific factors, such as crown gaps and tree surface saturation values, influence the amount of projected throughfall. Hourly meteorological and rainfall data from local sources are used for the simulations.

To estimate the value of rainfall intercepted by urban trees, we use stormwater management control costs based on minimum requirements for stormwater management in a particular region. For example: In Western Washington, for a 10-acre, single-family residential development on permeable soils it costs approximately $0.02779/gal to treat and control flows stemming from a 6-month, 24-hr storm event. In Fresno, the average cost for constructing and maintaining a typical detention/retention basin is $121,439/ac. With a 50% probability of filling 10 times in a 20-year period, the cost of detention/retention is $0.0077/gal. In Los Angeles, it costs approximately $0.0183/gal to treat sanitary waste, and we assume a similar cost for stormwater. Runoff control for very large events (100-year, 24-hr storm) was omitted, as trees' effective interception diminishes once surfaces have been saturated.

To calculate benefits, we multiply the management cost by gallons of rainfall intercepted after the first 0.1 inch has fallen for each event (24-hr without rain) during the year, depending on the region. Based on surface detention calculations, the first 0.1 inch of rainfall seldom results in runoff. Thus, interception is not a benefit until precipitation exceeds this amount.

and into drainages and natural waterways. However, water quality suffers when runoff carries contaminants such as oil, metals, or pesticides into streams, wetlands, lakes, and marine waters. Management of stormwater runoff can help reduce this pollution and make waterways healthy for people and fish.

Managing Stormwater Runoff with Trees

Some of the techniques that engineers have been using to manage stormwater runoff include infiltration, flow attenuation, retention, detention, extended detention, and undergrounding. See *http://www.co.ha.md.us/dpw* for more details. What you don't see here, and what engineers are beginning to consider, is the use of trees to retain water on site to slow the flow to waterways.

Our Center's research over the last few years has uncovered some very interesting facts about a tree's ability to retain water and how an urban forest contributes to the management of stormwater runoff.

Trees Retain Rainwater On Site—Our Initial Study

In an initial study in 1998 on individual trees, we found that during a rainfall event, precipitation is either intercepted by leaves, branches, and the trunk, or it falls directly through the tree to the ground. Intercepted water is stored temporarily on leaf and bark surfaces. After about 10 minutes, the tree's rainfall storage potential gets filled, and water begins to drip from leaf surfaces, flow down stem and trunk surfaces to the ground, or evaporate. We define *interception* as the sum of canopy surface water storage and evaporation.

Results are influenced by three factors: character and magnitude of the rainfall event, tree species and their architecture, and weather. Not every event will produce the same results because rainfall intensity and duration determine the interception process. Tree architecture, leaf and bark surface area, and routes to store the rainwater and control the flow all differ by tree species.

Temperature, relative humidity, net radiation, and wind speed control the length of time rainfall is retained in storage. For example, we found that trees stored more water during a 1-inch rainfall event that lasted two days versus one that lasted only two hours.

What is Interception?

Interception is the sum of canopy surface; water storage on leaves, branches, and trunk bark; and evaporation during rainfall events.

Urban Forests Make A Significant Contribution

After investigating individual trees we wanted to see how an entire urban forest influenced runoff volume. Taking the results of our initial study of individual trees, we created a canopy interception model to examine the storage capacity of the 6 million trees in Sacramento County, California. The results show that for just the land area covered by trees, the county's tree canopy intercepts 11.1% of the annual rainfall, close to reported values for hardwood forests. However, they account

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Editor: Laurie Litman, InfoWright

Fact Sheet #4: Control Stormwater Runoff with Trees

Points to remember

RAINFALL INTERCEPTION is influenced by:

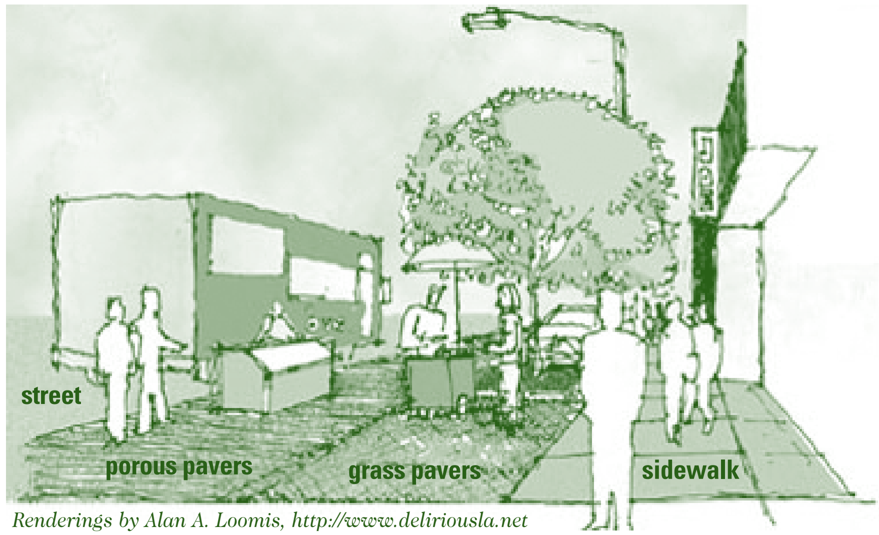
- Intensity and duration of the rainfall event
- Tree species—deciduous, broadleaf evergreen, or conifer
- Tree architecture—size, number of leaves, and arrangement of leaves and branches
- Weather—temperature, relative humidity, net solar radiation, and wind speed

TREES STORE MORE WATER during a 1-inch rainfall event that lasts two days versus one that lasts only two hours. Therefore:

- As compared to flood events, small storms are responsible for most of the annual pollutant loading of receiving waters
- Trees are most effective in intercepting rainfall during small events
- Urban forests are likely to produce more benefits through water quality protection than flood control.

ONE OF OUR STUDIES FOUND that a typical medium-sized tree can intercept as much as 2380 gallons of rainfall per year.

BROADLEAF EVERGREENS AND CONIFERS intercept more rainfall than deciduous species where winter rainfall patterns prevail.



Renderings by Alan A. Loomis, http://www.deliriousla.net

Redesign streets where trees work in combination with grass and porous pavers to retain water on site.

TREES WORK IN COMBINATION with other stormwater controls to produce a comprehensive solution to rainfall interception, runoff and landscape water use:

- Backyard cisterns capture roof runoff, and provide supplemental irrigation
- Swales hold overflow
- Bermed lawn-area retention basins facilitate infiltration
- Grates/drywells capture driveway runoff

STRATEGIES TO ENHANCE the urban forest and improve the control of stormwater runoff:

- Plant more trees in appropriate places
- Improve the maintenance of existing trees
- Plant species with a higher rate of growth where appropriate
- Plant species with architectural features that maximize interception
- Match trees (deciduous, evergreen) to rainfall patterns
- Plant trees in groves where possible
- Plant low water-use species
- Plant broadleaf evergreens where appropriate and avoid south-facing windows
- Use native plants, which, once established, can easily withstand summer dry seasons and reduce the need for supplemental irrigation.

In Oakland, California, the continuous tree canopy is estimated to intercept 4 inches of rain over one acre in a typical year— about 108,000 gallons.

NOTE: In looking for solutions to stormwater runoff it is important to consider an integrated approach that uses other water conservation, water retention, flood management, and pollution control strategies. Community solutions include but are not limited to: porous pavement, vegetated swales and filter strips, recharge areas under parking lots, holding tanks and cisterns under playfields, surface area holding ponds, turf grass filters, and riparian retention and treatment areas. For more information on these solutions see the TreePeople website at http://www.treepeople.org/trees/charrette.htm, and their book, *Second Nature: Adapting Los Angeles' Landscape for Sustainable Living,* edited by Patrick Condon and Stacy Moriarity.

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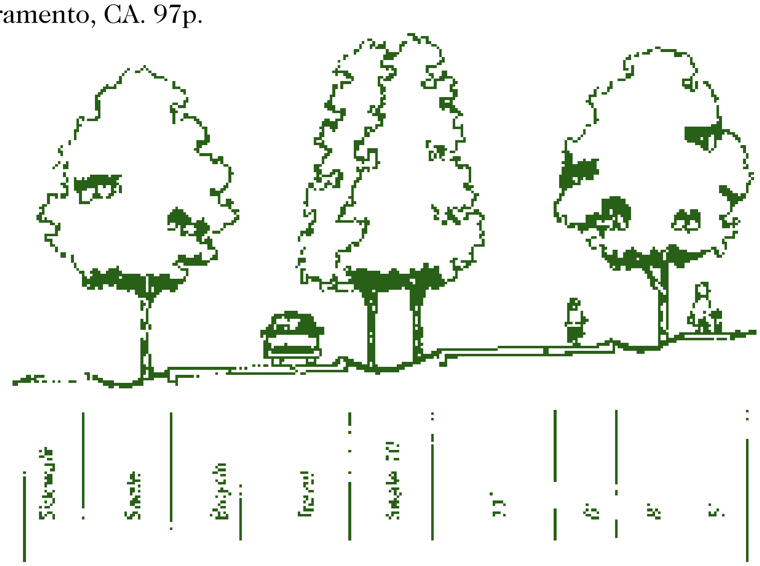

Incorporate stormwater treatment into street design by adding trees and swales. From Green Neighborhoods, a publication of NeighborhoodLAB, http://neighborhood.uoregon.edu/.

Visit our newly redesigned website at http://cufr.ucdavis.edu

Trees protect water and soil resources.

A healthy urban forest can reduce the amount of runoff and pollutant loading in receiving waters in four primary ways:

1) Through evapotranspiration, trees draw moisture from the soil ground surface, thereby increasing soil water storage potential.

2) Leaves, branch surfaces, and trunk bark intercept and store rainfall, thereby reducing runoff volumes and delaying the onset of peak flows.

3) Root growth and decomposition increase the capacity and rate of soil infiltration by rainfall and reduce overland flow.

4) Tree canopies reduce soil erosion by diminishing the impact of raindrops on barren surfaces.

Urban forests can dispose of waste water

Urban forests can provide other hydrologic benefits. For example, irrigated tree plantations or nurseries can be a safe and productive means of wastewater treatment and disposal. Reused wastewater can recharge aquifers, reduce stormwater treatment loads, and create income through sales of nursery or wood products. Recycling urban wastewater into green-space areas can be an economical means of treatment and disposal, while at the same time providing other environmental benefits.

Rainfall Interception Per Event (greater than 1/4")

Species	Dbh (in)	Crown projection (sq ft)*	Interception (gal) Summer	Winter	Total
Large					
Plane Tree[1]	16	1314	99	32	131
Camphor[2]	22	1227	62	62	123
Medium					
Chinese Pistache[1]	10	800	45	20	65
Jacaranda[2]	11	608	35	15	50
Small					
Crape Myrtle[1]	4	123	5	3	8
Podocarpus[2]	9	600	15	15	31

*Crown projection = Area under the drip line.
[1] Modesto, CA, winter rainfall pattern [2] Santa Monica, CA, winter rainfall pattern

for only 1.1% of the interception over the entire region because of the region's relatively low tree density and pattern of winter rainfall when deciduous trees are leafless.

The mix of tree species and their sizes influence interception. In Sacramento County, evergreen trees play the most important role in interception because most precipitation occurs in winter. Large trees with evergreen foliage contribute to greater interception than smaller, deciduous trees. In many climates with summer precipitation, deciduous trees make a substantial contribution to rainfall interception.

Planting more trees and improving maintenance of existing trees are important strategies that will help Sacramento, as well as many other communities, reduce the volume of stormwater runoff.

Shade yields less water use at power plants

Power plants consume water in the process of producing electricity. For example, coal-fired plants use about 0.6 gal/kWh of electricity provided. Trees that reduce the demand for electricity can also reduce water consumed at the power plant (McPherson et al. 1993). Precious surface water resources are preserved, and thermal pollution of rivers is reduced.

Rainfall and Tree Effectiveness

One effect that became clear in the Sacramento study was that urban forests become increasingly less effective at reducing stormwater runoff as the amount of precipitation per storm increases. Although trees reduce runoff, they may not be very effective for flood control.

Floods usually occur during major storm events, well after canopy storage has been exceeded. However, by substantially reducing the amount of runoff during less extreme events, urban forests can protect water quality. Small storms, for which urban forest interception is greatest, are responsible for most annual pollutant loading. Infrequently occurring large storms usually produce the greatest flooding damage, and although they may contain significant pollutant loads, their contribution to the annual average pollutant load is quite small (Chang et al. 1990).

Also, because of the infrequent occurrence of large storms, receiving waters have relatively long periods of recovery between events (Claytor and Schueler 1996). Therefore, urban forests are likely to produce more benefits through water quality protection than flood control.

How much rain are we talking about?

One inch of rain over one acre is about 27,000 gallons.

Taking the Next Step

Since trees are only a partial solution to managing stormwater runoff, the next step we've taken is to investigate other techniques to create a comprehensive approach that communities can take to keep most of their water from going down the drain. In collaboration with TreePeople in Los Angeles, we have selected two single-family sites in LA to evaluate four stormwater management techniques—cisterns, retention/detention basins, swales, and a driveway grate and drywell.

The sites we chose are adjacent lots with the same dimensions (50 ft wide by 150 ft deep). The techniques were installed on the treatment site only; the control site was left unmodified. The 3000-gallon cistern receives and stores filtered roof runoff and functions like a mini-reservoir for both runoff control and summer irrigation. The retention/detention basins (front and back lawns) retain roof runoff. The roof runoff infiltrates, evaporates, or overflows to the swale or to the street. The grate at the end of the driveway drains runoff into a drywell under the lawn, and the overflow is recharged in the retention/detention basin.

Preliminary Results

We have found that all stormwater runoff has been retained on the

(continued)

treatment site. We also found that the cistern storage provides about 10% of the annual water to irrigate the landscape. At the control site, runoff from half the roof and the entire driveway was discharged to the street.

Based on soil property measurements, both sites are situated on deep, sandy soil. The infiltration rate of these soils is greater than a 50-year flood event. What we don't know about this highly permeable soil: Does this on-site stormwater retention cause groundwater contamination? Are we just transferring the surface water problem to the groundwater?

We also don't know the effectiveness of on-site runoff retention in different geological settings, soil types, and landscape designs. These questions require further study.

> In Modesto, CA, each street and park tree was estimated to reduce stormwater runoff by 845 gallons annually, with a benefit valued at $7 per tree (McPherson et al. 1999). A typical medium-sized tree in coastal southern California was estimated to intercept 2,380 gallons annually, a $5 per tree benefit (McPherson et al. 2000). These studies showed that broadleaf evergreens and conifers intercept more rainfall than deciduous species where winter rainfall patterns prevail.

The Future

The goal of this project is to examine and model stormwater management techniques at the residential scale. The hydrologic and ecologic performance of this demonstration site will be monitored over the long term to help determine the problems and opportunities associated with treating each Los Angeles-area site as a mini-watershed.

By combining the model of these traditional techniques with our tree model, we will be able to more completely demonstrate the impact that a comprehensive solution will have on rainfall interception, runoff, and landscape water use. All of the rain does not have to go down the drain. Most, if not all, can be retained on site with a portion used for summertime irrigation.

—*Jim Geiger*

This research was a partnership between the Forest Service and University of California, Davis, performed by Dr. Qingfu Xiao, research affiliate with the Department of Land, Air, & Water Resources.

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Upcoming Presentations

August 27, 2002
Keynote Address: Municipal forestry benefit-cost analysis: a comparison of Modesto and Santa Monica, CA, by Greg McPherson. European Regional Conference of IUFRO, Copenhagen, Denmark.

September 13, 2002
A practical approach to assessing structure, function, and value of street tree populations in small communities, by Scott Maco. 2002 California Urban Forest Conference, Visalia, CA

September 13, 2002
Influencing local decision makers to invest in the urban forest, by Jim Geiger. 2002 California Urban Forest Conference, Visalia, CA

September 14, 2002
Planning for energy savings—using trees to reduce costs, cool communities, cool parking lots, schools, etc., by Jim Simpson. 2002 California Urban Forest Conference, Visalia, CA

September 25, 2002
Preserving the urban forest: creative sidewalk repair and replacement, by Greg McPherson with City of Los Angeles Street Tree Division. American Public Works Association Congress, Kansas City, MO.

September 27, 2002
Costs and benefits of urban trees in relation to smart growth, by Greg McPherson. Community Forestry at its Best, Nebraska City, NB.

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Hydrology & Earth System Sciences

Analysis of soil water dynamics in an agroforestry system based on detailed soil water records from time-domain reflectometry

N.A. Jackson and J.S. Wallace

Institute of Hydrology, Wallingford, OX10 8BB, United Kingdom
e-mail address for corresponding author: n.jackson@ioh.ac.uk

Abstract

Time domain reflectometry [TDR] was used to investigate the spatial and temporal variation in surface soil water dynamics under a number of types of vegetation, including both trees and crops grown in isolation, and grown together as an agroforestry system. The installation and operation of this technique are presented, and discussed in terms of its suitability to monitor rapid fluctuations in soil-water content in a spatially heterogeneous system such as that described in this experiment.

The relatively small sampling volume of each of the TDR waveguides permitted discrete measurements to be made of soil water content (θ_v). In the tree-only and tree+crop treatments, this revealed considerable variation in θ_v resulting from spatial redistribution of rainfall under the tree canopies, with a significant input to soil close to the base of the trees being made by stemflow, i.e. water intercepted by the tree canopy and channelled down the stem.

Over the experimental period (one rainy season) the TDR data suggested that net recharge to the soil profile in the sole crop system was 53 mm, almost 75% more than occurred in either of the two treatments containing trees, reflecting greater rainfall interception by the tree canopies.

Introduction

The experiment reported here formed part of a larger investigation of water use in an agroforestry system. Such water use studies are rare (Ong *et al.*, 1991), and tree/crop systems are often spatially complex in nature, with both the tree and crop canopies affecting rainfall distribution and input to the soil surface. Furthermore, in addition to most crop roots being concentrated in the top 0.5 m, Toky and Bisht (1992) found that root density was highest in the top 0.3 m for ten out of twelve agroforestry tree species investigated. Observations made as part of the larger field experiment confirmed that this was true for the tree and crop combination used in this study. For these reasons, time-domain reflectometry (TDR) was used to measure the rapidly occurring changes in surface soil water content over short lateral distances (<1 m) and depths (0 – 0.4 m), providing data for future modelling of the soil water balance.

TDR has been used for many years in the telecommunications industry for locating breaks in coaxial cable. Several authors have demonstrated the relationship between a soil's dielectric constant (K_a) and the volumetric water content (θ_v), and a more complete treatment of the theory of this relationship can be found elsewhere (Davis and Chudobiak, 1975; Topp and Davis, 1985; Ledieu *et al.*, 1986; Zegelin *et al.*, 1992). One advantage of TDR over many other forms of soil water measurement is that it lends itself to automated control and multiplexing, so that continuous data can be collected, with a frequency necessary to measure the dynamic nature of surface soil water storage.

Several authors have used TDR to investigate spatial and temporal variation in soil water content under maize (van Wesenbeeck and Kachanoski, 1988; Zhai *et al.*, 1990; Coelho and Or, 1996); they found persistent differences 'on' and 'off' crop rows. Similarly, several TDR studies have shown the effect that forest canopies impose on soil water content, both in semi-arid (Breshears *et al.*, 1997) and temperate situations (Nyberg, 1996; Ladekarl, 1998). However, few, if any, studies have been carried out using TDR to examine spatial and temporal variation in soil water content in combined tree and crop agroforestry systems.

Materials and methods

SITE DESCRIPTION AND EXPERIMENTAL DESIGN

The experiments were conducted at the Machakos field station of the International Centre for Research in Agroforestry (ICRAF) in Kenya. The station is situated about 80 km south-east of Nairobi at 1° 33′ South, 37° 8′ East, at about 1560 m altitude (Kibe *et al.*, 1981). The site has a south to south-west facing slope of about 22% and was covered by scrub dominated by *Acacia sp.* before the experiment was established in 1991. The slope runs downhill to the Maruba river about 200m below the site. The Machakos field station is typical of the surrounding Kenyan uplands (Scott *et al.*, 1971).

The soil consists of a series of shallow (0.2 to 2 m) reddish-brown to brown well-drained luvisols (FAO soil classification) varying in clay content over the profile, with a number of distinct horizons (Kibe *et al.*, 1981; Huxley *et al.*, 1989). Water release curves for the surface (0–0.4 m) soil layers at the field site, were determined from intact soil cores (Soil Survey, UK). These confirmed that the soil was a typical sandy clay loam and was unlikely to exhibit soil water contents lower than 0.05 $m^3\ m^{-3}$, the threshold below which most commonly used TDR calibration equations are unable to determine θ_v accurately (Zegelin *et al.*, 1992).

The soil is underlain by layers first of weathered and then coherent rock (gneiss) at varying depths. A band of very shallow soils (0.2 to 0.6 m deep) ran across the site from the top north-west corner towards the bottom south-east corner. Soils were generally deeper (0.7 to 1.5 m) above and below this band (Wallace *et al.*, 1995).

This experiment formed part of an agroforestry trial conducted by ICRAF and the Institute of Hydrology at Machakos established in October 1991, details are given elsewhere (Wallace *et al.*, 1995). Briefly, plots of size 20 m × 20 m were planted either with *Grevillea robusta*, a popular upperstorey tree species in East Africa (ICRAF, 1995), grown on their own (T_d treatment), maize planted on its own (C_g treatment), or the two components grown together (CT_d treatment). These planting arrangements are shown in Fig. 1. Maize was planted after the onset of the rains, when the entire ground surface was prepared with hand hoes, in rows 1 m apart, 0.3 m between plants. The tree canopies were regularly pruned during the course of the experiment following local farming practice, maintaining similar sized canopies on all trees.

INCIDENT RAINFALL

Annual rainfall has a bi-modal distribution, with a short rainy season of 265 mm usually lasting from late October to late December, and a longer rainy season of 345 mm running from late March to the end of May. Monthly rainfall peaks in April and November and there is little rainfall in July, August and September. Machakos district has a large inter-annual variation in monthly and seasonal rainfall. The climate is on the boundary between sub-humid and semi-arid (Huxley *et al.*, 1989).

Incident rainfall was measured using a tipping-bucket raingauge (200 mm diameter) positioned uphill from the plots and approximately 20 m from the nearest trees. Rainfall was measured every 10 minutes and cumulative hourly values were stored on a data logger (Campbell 21x, Campbell Scientific Instruments, USA).

TIME DOMAIN REFLECTOMETRY: INSTALLATION

The TDR system (Soil Moisture Corp. Trase™ System I, Goleta, CA, USA) installed in this agroforestry trial used buriable waveguides or 'sensors', of a three-wire design, 0.2 m long, with a space of 15 mm between the wires. Three-wire probes simulate a coaxial line directly and therefore do not need additional impedance matching transformers or 'baluns' (Topp, 1992). A sensor length of 0.2 m was chosen to provide an acceptable degree of resolution in θ_v (0.01 $m^3\ m^{-3}$) when used with long (30 m) cables. Using shorter sensors with long cable lengths would have introduced an underestimation of K_a and hence reduced the resolution of estimates of θ_v (Heimovaara, 1993).

60 TDR sensors were installed on 5 April 1994 by digging small soil pits down-slope of the sensors' desired location (see Fig. 1). The TDR sensors were multiplexed to a central signal processing and recording unit. Waveforms from the sensors were inspected manually to ensure that each was working correctly before the soil from each pit was refilled carefully and compacted to approximate the undisturbed soil bulk density. Each TDR 'location' comprised a group of four sensors, inserted horizontally into the upslope soil face, at depths 0.05, 0.15, 0.25 and 0.35 m.

Three sensor groups (12 sensors) were located in one of the C_g plots, each group positioned midway between the rows of maize, each sampling the same area of soil. In each of the T_d and CT_d plots, six sensor groups (24 sensors) were installed at various distances (0.3, 1.0, 1.5, 1.8, 2.0 and 2.5 m, see Fig. 1) from the base of trees of average height, basal diameter and projected canopy area.

The radial distances of the TDR sensor groups meant that the soil water contents measured by each group were representative of a different sized fraction of the area occupied by each tree. Therefore, the overall area (12 m^2) was subdivided into concentric rectangular zones around the tree, with the inner and outer boundaries of each zone given by the midpoints between the radial distances of each of the TDR sensor groups (see Table 1). Each zone had the same proportions as the 4 × 3 rectangle occupied by each tree. The areal average soil water content was therefore a weighted mean value, using the percentage area of each zone as the weighting factor.

The limited number of channels available to multiplex the TDR sensors prevented spatial replication within the

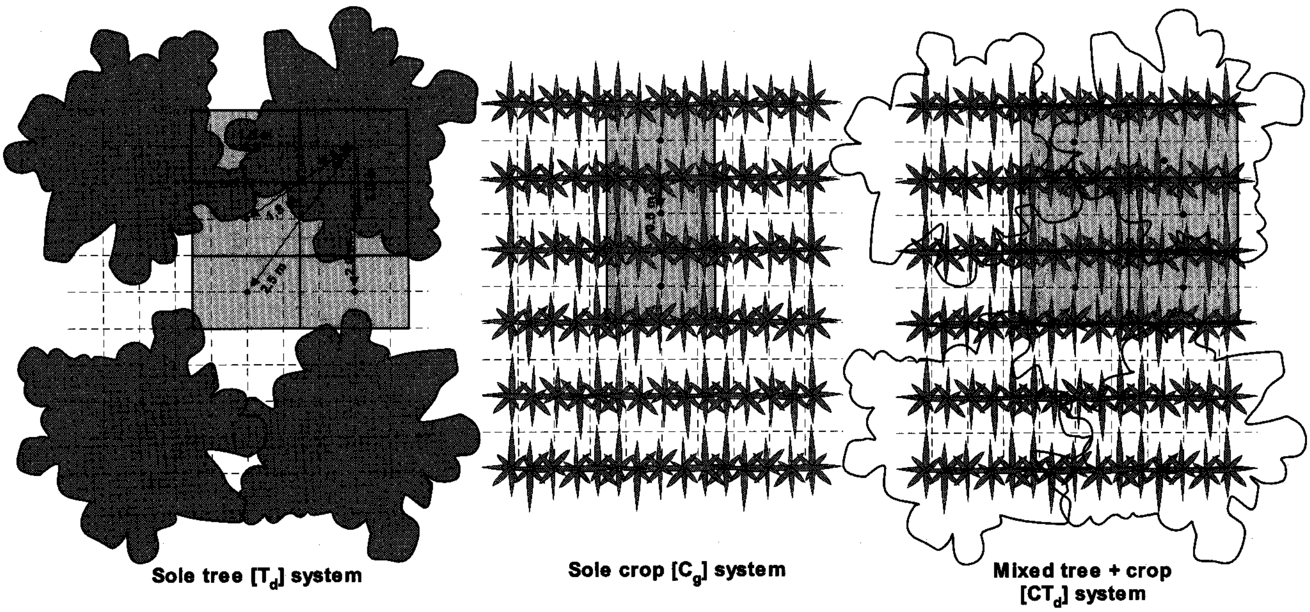

Fig. 1. *A schematic representation of the layout of the three treatments in which TDR sensors, throughfall and stemflow gauges were deployed. Each of the small squares is 0.5 m × 0.5 m, and each of the shaded blocks is 1.5 m². TDR sensors were deployed midway between maize rows in sole-planted maize. Otherwise, TDR sensors were deployed at various radial distances (shown) from the base of a tree in both the sole-tree and tree+crop treatments. Gauges measuring rainfall interception were placed in positions identical to the TDR sensors in all three treatments.*

three treatments, but to attempt to account for possible differences in surface soil texture or composition, the entire network of TDR sensors was moved three times during the experiment and reinstalled in the same arrangement (i.e. between crop rows and/or around trees). Each time the sensor network was relocated, the same trends in soil water content were observed, suggesting that these were due to treatment effects rather than variations in soil conditions.

All sixty TDR sensors were logged hourly from 5 April 1994 onwards. Waveforms from each sensor were interpreted automatically by the software in the central processing unit and stored as volumetric water contents (θ_v, m^3 m^{-3}). The data were downloaded every few days using a portable computer, and were inspected manually to remove occasional spurious readings. The noise component common to TDR data was reduced by taking a 7-point moving average of the hourly data, following the procedures of Zegelin *et al.* (1992), and Baker and Spaans (1994). The variance between the moving average and the measured water contents was typically less than 0.5 mm. Volumetric water contents (θ_v) were converted to storage

Table 1. The way in which the 12 m² occupied by each tree in the T_d and CT_d treatments (4 × 3 m planting) was subdivided into concentric zones, the boundaries of which were the midpoints between the TDR sensors. The percentages of the total area of each of the zones were used to obtain weighted areal average soil water contents.

Radial distance of TDR sensor	Inner boundary	Outer boundary	Rectangular area of zone around tree [a]	Proportional land area
(m)	(m)	(m)	(m²)	(%)
0.3	0.00 [b]	0.65	0.81	6.76
1.0	0.65	1.25	2.19	18.24
1.5	1.25	1.65	2.25	18.75
1.8	1.65	1.90	1.59	13.25
2.0	1.90	2.25	2.88	24.00
2.5	2.25	2.50	2.28	19.00

[a] Each zone had the same proportions as the 4 × 3 rectangle occupied by each tree.
[b] The innermost zone was considered to stretch from the centre of the tree to the midpoint between the sensors at 0.3 and 1.0 m.

values (S) in mm, integrating the values from each of the four sensor depths in each 0.4 m profile.

TIME DOMAIN REFLECTOMETRY: CALIBRATION

The empirical equation of Topp *et al.* (1980) relating K_a and θ_v:

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} (K_a) - 5.5 \times 10^{-4} (K_a)^2 + 4.3 \times 10^{-6} (K_a)^3 \quad (1)$$

was shown to work in various soils of different textures and compositions, although more recent attempts have been made to derive TDR calibrations that incorporate soil physical aspects (Ledieu *et al.*, 1986). The TDR system in the present study uses a copyrighted 'lookup table' (Soil Moisture Corp., 1991) based on time delay factors and subsequent K_a values. The Trase™ calibration table follows the empirical model of Topp *et al.* (1980) closely but allows for variation in soil type (Skaling, 1992). Zegelin *et al.* (1992) stated that the 'universal' empirical calibration derived by Topp *et al.* (1980) worked well in almost all soils except those with a significant organic component; however, even in light textured soils, there might be a systematic deviation from the relation below soil water contents of 0.05 m^3 m^{-3} because the dielectric component of individual soil components then becomes important.

To determine whether the 'built-in' Trase™ lookup table provided an accurate enough estimation of soil water content at Machakos, it was compared with the Topp *et al.* (1980) calibration, using both intact cores of soil taken from the field (125 mm diameter, 250 mm deep) and prepared 'test cells' filled with dried field soil (60 mm × 60 mm × 250 mm) repacked to the mean soil bulk density. The test cells were wetted gradually from beneath by placing them on a bed of wet sand until they reached the desired volumetric water content. The soil water content of the test cells was measured gravimetrically by drying the soil at 80 °C until constant weight had been determined. The soil water content was then expressed volumetrically (m^3 m^{-3}).

The TDR signals from both the cores and the test cells were measured with the same type of waveguide that were used in field measurements, inserted vertically into the soil. The dielectric constant of each test cell or core was determined by the TDR central unit, and these K_a values were used to calculate volumetric water contents (m^3 m^{-3}) using both the Trase™ system lookup table, and Eqn. 1. The values of θ_v calculated by each method were plotted against oven-dried determinations of θ_v and the relationships are shown in Fig. 2.

Both methods estimated θ_v very well, accounting for more than 96% of the scatter, and with sample variances around the 1:1 relationship of 0.01 and 0.03 m^3 m^{-3} for the Topp and Trase™ calibrations, respectively. Given that the difference between the two methods was similar to the limit of sensitivity of the instrument (0.01 m^3 m^{-3}), and to

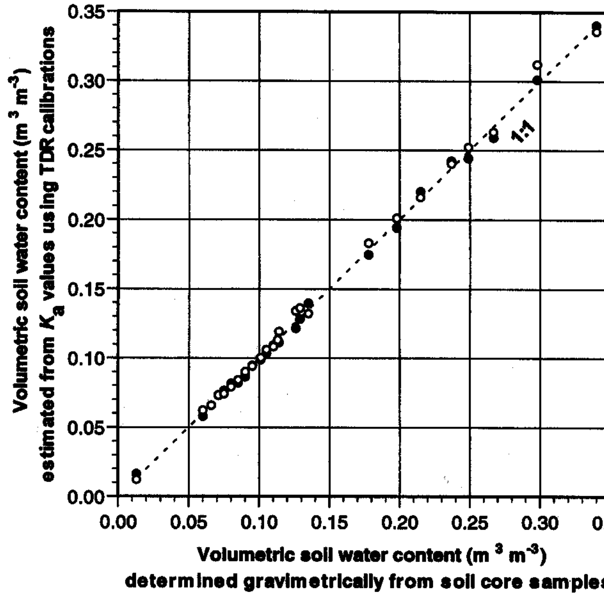

Fig. 2. *Comparison between soil water contents determined gravimetrically and estimated using the built in Trase™ (○) and Topp (●) TDR calibrations. Data were obtained from repacked soil in laboratory test cells and from intact soil cores taken from the field.*

avoid an extra step in data analysis, the Trase™ method was used to estimate θ_v.

CANOPY RAINFALL INTERCEPTION

To compare changes in surface soil water content to varying water input, matching measurements of rainfall interception by the tree and crop canopies were made. For reasons of cost, manually recorded rather than tipping bucket raingauges were used. These were measured after every rainfall event. Siting the gauges too close to the TDR sensor groups would have rendered the purpose of the study impossible, i.e. recording rapid changes in surface soil moisture.

Therefore a matching interception gauge for each TDR sensor group was installed in an equivalent position around a tree of equal height, basal diameter and projected canopy area, no more than 3 m away (or ~ 2 m further along the same crop rows in the case of the C_g plots). As with the TDR sensor groups, the network of interception gauges was moved at regular intervals to other trees in the plots as a form of temporal replication.

Even with canopies pruned to a consistent size and shape, the possibility remains of small scale variation in interception between tree canopies, e.g. due to 'canopy drip' from branches directly over the raingauge. However, the results of a larger interception study in the same plot (Jackson, 1999) determined that although there was significant variation in interception at different radial positions away from the tree, the variation between gauges at similar positions was low (less than 5%).

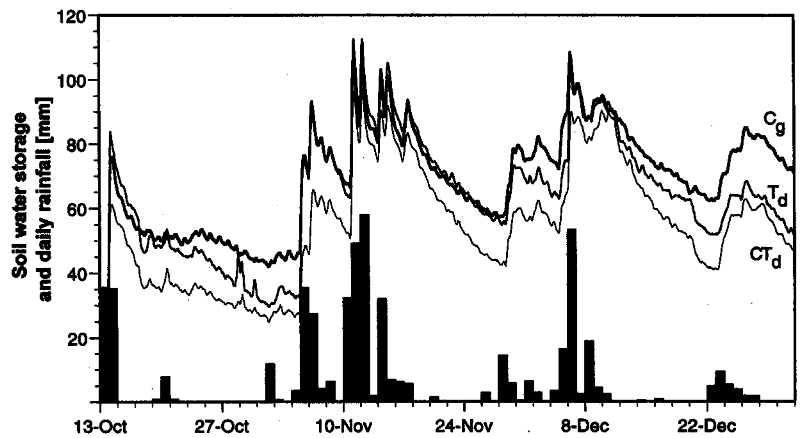

Fig. 3. *Changes in the integrated water storage (S) in the top 0.4 m soil profile in the three treatments, C_g, T_d and CT_d (thick to thin lines, respectively) between 13 Oct and 31 Dec, 1994. The data are shown as weighted means of the integrated 0.4 m profiles (see text for details) at all six TDR positions in the T_d and CT_d treatments (see Fig. 1), and the mean of the three TDR positions in the C_g plot. Corresponding daily rainfall is shown below the TDR graph.*

One effect of the tree canopies, in particular, is to channel some of the rainfall intercepted by the foliage down the trunk and into the soil immediately surrounding the base of the tree. Obviously, the degree to which this occurs is influenced strongly by the shape of the tree canopy but in the case of *Grevillea* the volumes of water involved can be substantial. Nine stemflow gauges were installed on trees in each of the T_d and CT_d plots. The gauges comprised a flexible plastic collar which was sealed to the trunk of the tree with a non-toxic silicone compound about 0.75 m above the ground. The collars drained to plastic jerry-cans of 35 l capacity, which were measured at the same time as the interception gauges.

Observations made on trees without gauges showed that when the stemflow water reached the soil surface, all infiltrated close to the base of the tree (< 0.5 m), i.e. well within the 1.5 m^2 block of soil containing the tree shown in Fig. 1. On this basis, stemflow was converted to mm equivalents using a distribution area of 1.5 m^2, and was combined with the throughfall measurements made over this block of soil.

Results and discussion

TREATMENT EFFECTS ON 0–0.4m PROFILE WATER STORAGE (S)

It was important to quantify the surface soil water dynamics of the agroforestry system in comparison with the conventional tree-only and crop-only alternatives. Farming practices in semi-arid regions, such as the maize-only system used in this study, often use less than 50% of the rainfall input to the soil surface (Ong *et al.*, 1991; Wallace, 1991), the rest being lost gradually during the dry interseasonal periods under conventional crop-only systems, by soil evaporation from the bare soil, and through drainage.

In a simultaneous study (Jackson *et al.*, 1999), neutron probe measurements made over the entire profile (0–2 m) showed that the soil below 0.4 m hardly recharged at all following rainfall. In addition, Smith *et al.* (1999) found that more than 50% of the rooting system of the *Grevillea* trees was concentrated in the top 0.4 m of soil. Our data suggest that these roots utilised much if not all of the incoming rainfall during these seasons, and prevented the lower soil layers from recharging. For these reasons, rapid changes in the 0–0.4 m soil layer measured by the TDR sensors are particularly important.

The mean (0–0.4 m) water storage values for the C_g, T_d and CT_d treatments are plotted against time in Fig. 3, for part of the 1994 short rains. The data are presented as averages of three sensor groups (in the C_g treatment) or weighted areal averages of six groups in the T_d and CT_d treatment. Initial water storage just before the onset of the rains (12 Oct 1994) was similar for all three treatments, at 18.4 ± 1.7 mm, 18.0 ± 1.5 mm and 18.6 ± 0.3 mm for the CT_d, T_d and C_g plots, respectively.

Rainfall interception was greater under the tree canopies than under the sole crop (Table 2), leading to lower soil water inputs in the T_d treatment, and the lowest occurring in the CT_d treatment, where increases in water storage following rainfall were on average 15% lower than in the C_g plots ($p \leq 0.05$). Hourly increases in water storage in the CT_d plots ranged between 0.1 and 6.8 mm h^{-1} and were lower during each rainfall event than those for the T_d and C_g plots, which ranged from 0.1 to 9.3 mm h^{-1}, and from 0.1 to 8.1 mm h^{-1}, respectively ($p \leq 0.05$).

After rainfall, there were distinct differences between treatments in terms of the rate of decrease in soil water content. The absolute drying rates for the agroforestry plots, ranged between 0.1 and 1.7 mm h^{-1} over the period of study. These rates were lower after each rainfall event than those for the sole tree plots, and sole crop plots,

Table 2. Cumulative rainfall (ΣP_g) and net rainfall (combined throughfall and stemflow: ΣP_n) in the C_g, T_d and CT_d treatments, recorded between Oct 12 and Dec 31, 1994. Data are given as mm of water and ΣP_n as a percentage of ΣP_g.

	Cumulative net rainfall (ΣP_n) below tree/crop canopies					
Cumulative rainfall off-plot (ΣP_g) (mm)	Sole crop, C_g (mm)	Sole crop, C_g (% ΣP_g)	Sole tree, T_d (mm)	Sole tree, T_d (% ΣP_g)	Tree+crop, CT_d (mm)	Tree+crop, CT_d (% ΣP_g)
512	463	90%	421	82%	390	76%

which ranged from 0.1 to 2.4 h^{-1}, and from 0.1 to 2.6 h^{-1}, respectively ($p \leq 0.05$).

The 'rising' and 'falling' portions of the TDR time courses were separated and are presented in Fig. 4 as cumulative gains and losses of surface soil water in each of the treatments. Throughout the period, water storage was greatest in the C_g treatment at 414 mm, slightly lower in the T_d plots at 402 mm, and lowest when the trees and crops were grown together in the CT_d treatment at 346 mm.

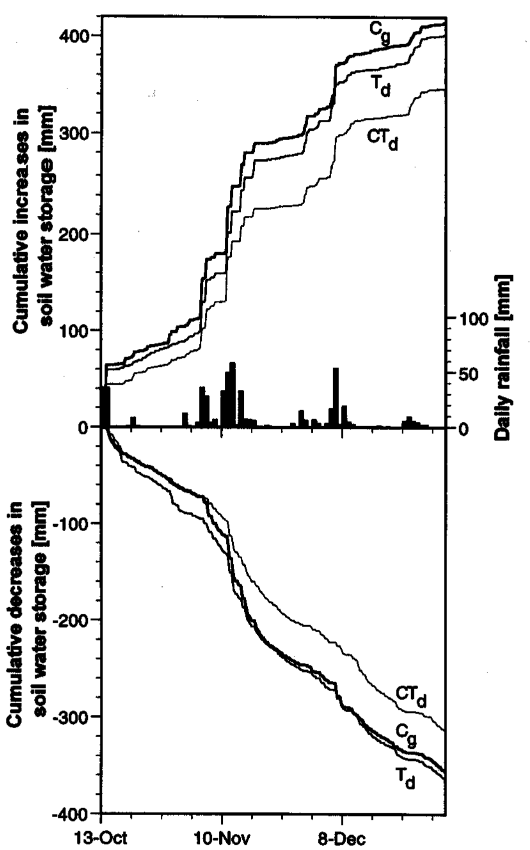

Fig. 4. *Data from Fig. 3 plotted in terms of cumulative gains and losses in water against time in the C_g, T_d and CT_d profiles (thick to thin lines, respectively) between 13 Oct and 31 Dec, 1994. Corresponding daily rainfall is shown below the TDR graph.*

Cumulative losses of water were initially greater in the T_d plots than in either the C_g or CT_d plots, which may reflect higher transpiration rates from the larger trees in the T_d plots (Lott *et al.*, 1997). Large gains in water in the C_g plots during this initial period, with correspondingly small losses, may be due in part to the fact that the C_g maize plants were quite small and transpirational demand was low. As the C_g crop cover increased cumulative losses more closely matched those from the T_d treatment.

By the end of the period studied, the cumulative losses from the C_g, T_d and CT_d plots were 359 mm, 364 mm and 314 mm, respectively. By the end of the rainy season (late Dec 94), net profile storage increased by 55 mm in the C_g plots, by 38 mm in the T_d plots and by 32 mm in the CT_d plots. Cumulative rainfall (ΣP_g) during the period shown was 512 mm.

SPATIAL HETEROGENEITY IN RAINFALL AND SOIL WATER STORAGE UNDER TREE AND CROP CANOPIES

During the experiment there was no significant difference between the three positions in the sole crop plot in terms of either rainfall input or surface soil water content. However, van Wesenbeeck *et al.* (1988) showed that, under a maize canopy, the inter-row soil profile was significantly wetter than the soil directly beneath the crop. This spatial variation was attributed to differences in soil bulk density (and subsequent infiltration) caused by mechanical double-disk seeding at the time that the maize crop was planted.

In this study, as the entire ground surface was dug over prior to planting the crop, such artificial variations in bulk density should not have been present. Nevertheless, to ensure that placing the TDR sensors between crop rows neither over- or underestimated soil water content, periodic measurements of θ_v were made 'on' and 'off' crop rows using a hand-held capacitance probe (Robinson and Dean, 1993); no significant variation in θ_v was detected. This lack of spatial variation in θ_v suggests that any redistribution of rainfall via stemflow by the maize plants (as observed by Parkin and Codling, 1990) was either minimal, or was compensated for by localised surface runoff,

Table 3. Cumulative net rainfall (combined throughfall and stemflow: ΣP_n) recorded between Oct 12 and Dec 31, 1994 at various locations (see Fig. 1) below the tree and crop canopies in the T_d and CT_d treatments. Data are given as mm of water and ΣP_n as a percentage of cumulative gross rainfall (ΣP_g) during the period, which was the same as in Table 1, i.e. 512 mm.

	Cumulative net rainfall (ΣP_n) below tree/crop canopies					
	0.3 m from tree		1.5 m from tree		2.5 m from tree	
Treatment	(mm)	(% ΣP_g)	(mm)	(% ΣP_g)	(mm)	(% ΣP_g)
Sole tree (T_d)	399	78%	347	68%	481	94%
Tree + crop (CT_d)	421	82%	312	61%	469	92%
T_d/CT_d average	410	80%	330	64%	475	93%

redistribution in the surface soil layers, and/or through soil evaporation and abstraction by crop roots.

The effect of adding trees to a cropping system, as in the case in agroforestry systems, may be to increase rainfall interception, and thereby reduce the amount of rainfall that reaches the ground and is therefore, available to the crop (Wallace *et al.*, 1995). This makes the system more spatially complicated and makes it more difficult to model changes in surface θ_v that result from rates of evaporation, drainage and abstraction which have been modified by the presence of trees. In this experiment, significant differences in both rainfall input and surface soil water content were observed beneath the trees, and the effect of the tree canopies on rainfall redistribution and profile water storage (S) was examined. Table 3 summarises the amount of water reaching the surface at distances 0.3, 1.5 and 2.5 m from the tree in both the T_d and CT_d plots. Stemflow accounted for a little over 6% of incident rainfall, and was added to throughfall measurements made closest to the trees (as mentioned earlier).

Although there were slight differences between the two tree treatments, the lowest interception occurred at 2.5 m, midway between four trees (see Fig. 1). The fact that there was any difference between P_g and P_n at this position suggests that, as reported in previous interception studies (Aldridge, 1975; Herwitz and Slye, 1995), some of the rainfall must have been inclined away from vertical fall paths and was therefore being intercepted by the adjacent tree canopies. P_n was greater at 0.3 m distance than at 1.5 m (midway between two trees along the contour line) due largely to the additional soil water input from stemflow.

Figure 5 shows the variation in the amount of water stored in the top 0.4 m of soil as determined by TDR sensor groups located at 0.3, 1.5 and 2.5 m from the tree in one of the T_d plots. Initial water storage before the onset of the rains (12 Oct 1994) was 14.2 ± 0.8 mm, 9.8 ± 1.1 mm and 24.7 ± 0.7 mm at the three positions, respectively. There was a good agreement between increases in soil water storage and the ranking of interception values shown

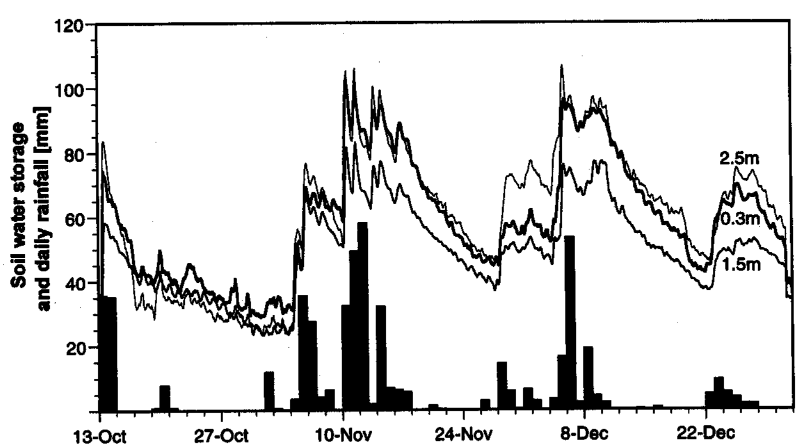

Fig. 5. *Changes in the integrated water storage (S) in the top 0.4 m soil profile in three positions in one of the CT_d plots between 13 Oct and 31 Dec, 1994. Data are from TDR sensors at 0.3, 1.5 and 2.5 m (thick to thin lines, respectively) from the base of the tree (see Fig. 1). Corresponding daily rainfall is shown below the TDR graph.*

in Table 3. The TDR sensor groups at 0.3 m and 2.5 m from the tree showed greater increases in storage following rainfall (ranging between 0.1 and 24.7 mm h^{-1} and from 0.1 to 19.8 mm h^{-1}, respectively) than did the soil 1.5 m along the tree line (see Fig. 1), ranging from 0.1 to 14.2 mm h^{-1}.

Following rainfall, the rate at which soil water content decreased was similar for both positions closer to the tree, ranging from 0.1 mm h^{-1} to 11.1 and 9.4 mm h^{-1} at 0.3 m and 1.5 m, respectively. Drying rates were consistently faster at 2.5 m distance, ranging from 0.1 to 16.9 mm h^{-1}. It may be that high bare soil evaporation rates at this position (Jackson and Wallace, 1999) were the driving force behind declines in soil water content.

The 'rising' and 'falling' portions of the TDR time courses were separated, in the same fashion as for Fig. 4, and are presented in Fig. 6. Substantial differences in both cumulative gains and losses of surface soil water were observed at each of the positions around the tree. Over the course of the rainy season, water storage was greatest at 2.5 m (414 mm), and more than 150 mm lower 1.5 m along the tree line at 351 mm. The soil directly beneath the tree (0.3 m) showed cumulative water gains of 442 mm, which suggested a significant input was made by stemflow infiltrating at the base of the tree.

Trends in cumulative losses of water reflected the differential inputs of soil water at each of the positions, with the greatest drying occurring midway between the trees at 2.5 m. This may be due mainly to lower rates of evaporation from the shaded soil close to the tree (Jackson and Wallace, 1999), but lower root densities close to the tree (Smith *et al.*, 1999) might have led to differences in soil water abstraction. Overall, the cumulative losses were 405 mm, 332 mm and 497 mm, at 0.3, 1.5 and 2.5 m from the tree, respectively, with net profile storage increasing by 12 mm, 19 mm and 16 mm.

The arrangement of four TDR waveguides at various depths at each location allowed a more detailed investigation of the infiltration dynamics in the Machakos soil. Figure 7 shows two examples where a wetting front devel-

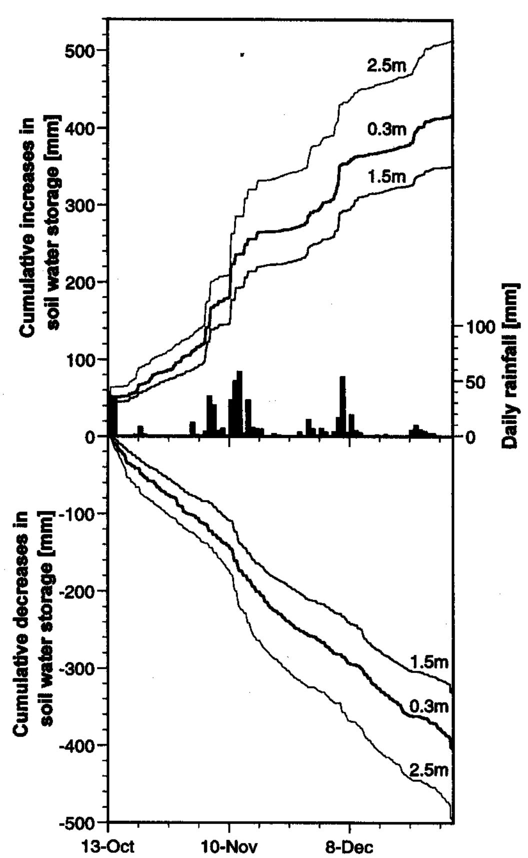

Fig. 6. *Data from Fig. 5 plotted in terms of cumulative gains and losses in water against time for the TDR sensor profiles at 0.3, 1.5 and 2.5 m (thick to thin lines, respectively) between 13 Oct and 31 Dec, 1994. Corresponding daily rainfall is shown below the TDR graph.*

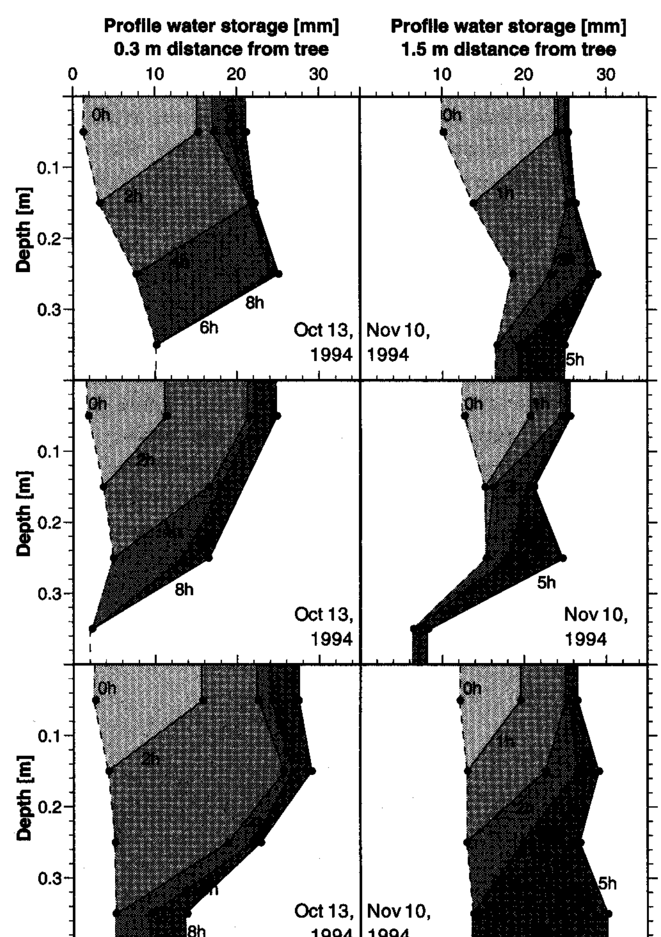

Fig. 7. *Progression of soil-water storage profiles at three distances (0.3, 1.5 and 2.5 m) from the base of a tree in one of the sole tree (T_d) plots during and following two rainfall events. The three graphs on the left-hand side show the development of wetting fronts through relatively dry soil, while the right-hand series shows profiles that developed when the antecedent soil-water contents were higher (see Table 4).*

Table 4. Comparison of the amount of water infiltrating the soil at three distances from the base of the tree in one of the CT_d plots (shown in Fig. 7) with the amount of incident rainfall as measured by the automatically logged raingauge.

Rainfall event on 13–14 October 1994

Time (h)	Cumulative rainfall (mm)	Initial values (S_i) and cumulative changes in integrated profile water storage (S) in mm at: 0.3 m from tree 22.5 (S_i)	1.5 m from tree 12.8 (S_i)	2.5 m from tree 17.3 (S_i)
0	0	0.0	0.0	0.0
1	2.6	0.1	0.2	0.3
2	17.4	15.9	9.5	13.1
3	49.2	31.0	19.3	37.3
4	66.8	38.8	23.0	63.5
5	68.2	56.4	31.9	65.3
6	68.8	52.5	41.9	65.3
7	69.2	50.8	43.2	68.6
8	70.2	50.0	45.5	67.9

Rainfall event on 10–11 November 1994

Time (h)	Cumulative rainfall (mm)	Initial values (S_i) and cumulative changes in integrated profile water storage (S) in mm at: 0.3 m from tree 59.3 (S_i)	1.5 m from tree 49.8 (S_i)	2.5 m from tree 52.1 (S_i)
0	0	0.0	0.0	0.0
1	9.8	13.9	8.0	7.4
2	22.6	32.4	13.7	22.7
3	32.4	37.5	20.0	33.4
4	45.5	43.4	24.0	41.0
5	67.8	45.7	30.0	60.5

ops and moves down through the 0.4 m profile, at 0.3, 1.5 and 2.5 m from the base of a tree in one of the CT_d plots. The first set of graphs is a typical example of the soil wetting up after a long dry period, and shows the infiltration after an overnight rainfall event of 70.2 mm (13–14 Oct, 94). The mean initial profile water storage (S_i) at the three positions was 17.5 ± 4.9 mm.

The second set of graphs represents the situation where the initial profile storage was higher (mean S_i = 53.7 ± 5.0 mm), and shows the infiltration following another overnight rainfall event of 67.8 mm (10–11 November, 1994). The duration of rainfall (t) is shown for each of the profiles (t = 0,2,4,6 and 8 h for the first set of graphs and t = 0,1,2,3 and 5 h for the second series).

In the first case where a dry soil profile is gradually wetting up, the wetting front moved down through the soil more rapidly at 2.5 m from the tree than at the other two positions; after 4 hours of rainfall, the front had almost reached the bottom of the 0.4 m profile, and 6 hours after the rain started the sensors at the 0.35 m depth had detected the wetting front. In comparison, neither of the other two profiles had wetted up completely, even 8 hours after the start of the rainfall.

In the second case, where values of S_i were higher, the rates of wetting up were much faster at all three positions. As initial profile storage values were higher, less water was needed in each case to bring the soil water contents up to the values where hydraulic conductivity was sufficient for gravitational flow down through the soil to match the rainfall intensity. In this situation, the soil near the base of the tree (0.3 m) wetted up faster than that at 2.5 m, although the final profiles of S were quite similar 5 hours after the rainfall started. The soil at 1.5 m from the tree did not wet up to the same degree as the other two positions and the wetting front had only just reached the bottom of the profile 5 hours after the start of the rain.

Table 4 shows the changes in the integrated soil profile water storage during these two rainfall events. It summarises the data shown in Fig. 7 and demonstrates that the soil around the base of the tree (0.3 m) wetted up more rapidly than the soil either in line with the trees (1.5 m), or out in the open (2.5 m). The data suggest that significant amounts of water may reach and infiltrate the soil close to the tree by indirect means. Stemflow is usually believed to be of little importance when the water balance is calculated on an areal average basis. However, stemflow is not evenly distributed over the area beneath a tree canopy but often concentrates significant quantities of water (Prebble and Stirk, 1980) and nutrients (Belsky *et al.*, 1993) into a small area around the base of a tree.

It is possible that the observed differences during each event in transmission zone water content between the various positions may be explicable in terms of different infiltration rates, and therefore the hydraulic conductivity needing to be attained in order for gravitational flow to match rainfall input. Such differences in infiltration rate and soil bulk density might result from the presence of tree roots, as reported by Zinke (1961) and Eschner (1967).

Concluding remarks

The choice of time domain reflectometry using buriable waveguides in this experiment provided the means to follow the spatial and temporal variations in surface soil-water content (θ_v) and storage (S). From the trends observed, and accepting the restrictions imposed by limited replication, the data *suggest* that significant differences in recharge may develop when trees are incorporated into an existing cropping system.

The data presented here form part of a larger dataset combining deep profile measurements (Jackson *et al.*, 1999) soil evaporation (Jackson and Wallace, 1999; Wallace *et al.*, 1999) and rainfall interception (Jackson, 1999), which, when taken together, suggest that trees in agroforestry systems may be able to utilise water resources that would otherwise be lost during intervals between cropping seasons, through soil evaporation and drainage.

When considering a spatially heterogeneous system like this, it is important to realise that the heterogeneity exists not just in two dimensions, but in three, taking into account both the crops and upperstorey tree species. The combination of interception measurements and the TDR technique in a small study like this, has demonstrated how variation in soil-water inputs across the area between trees can be measured. Further experiments with greater degrees of replication are required to shed more light on this matter.

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