San Francisco Bay Area State of the Urban Forest Final Report

By
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USDA Forest Service, Pacific Southwest Research Station

—December 2007—

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Acknowledgements

The authors are indebted to Klaus Scott, California Air Resources Board, for preliminary analysis and conversion of tree cover or leaf area by land use for Sacramento, San Francisco and Oakland. They would also like to acknowledge Drs. Qingfu Xiao and Chelsea Wu, Department of Land, Air, and Water Resources, University of California Davis, for their invaluable aid with the GIS database and image analysis. John Melvin (CAL FIRE) provided valuable comments on a draft version of this manuscript.

Executive Summary

The nine county San Francisco Bay area contains over 200 municipalities and approximately 6.7 million people. Rapid growth, especially in outlying areas, is accelerating air pollution, water, and energy demand problems. These problems urgently need solutions. Urban forestry is integral to land use planning, mitigating water shortages, conserving energy, improving air quality, enhancing public health programs, increasing land values and local tax bases, providing job training and employment opportunities, reducing costs of city services, and increasing public safety. Although any single tree benefit may be small, the sum of benefits is significant when it comes to mitigating the environmental impacts that result from converting natural land cover to built environments.

The three goals of this study were (1) to describe the region's existing and historic urban forest structure, (2) to quantify the value of ecosystem services the current forest provides, and (3) to estimate future benefits based on possible expansion of the urban forest. This information will enhance our understanding of the relevance of urban forests and of the extent to which they impact the environmental and economic health of Bay area communities.

Part I. Canopy Cover Change 1984–2002

Historic changes in canopy cover, as well as impervious (rooftops, paving) and pervious (turf, bare soil) land cover for urban areas of the nine county region were mapped based on satellite imagery from 1984, 1995, and 2002. Spectral mixture analysis, refined using other techniques, was used, and accuracy was assessed by comparison with high-resolution aerial photography. Urban area boundaries were defined by the 2000 Census.

The urban environment in the San Francisco Bay area has rapidly expanded into predominately rangeland and agricultural areas. A population increase of 30 percent has driven a 73-percent increase in urban area. During the 19-year study period, the canopy cover increase of 10 percent did not keep up with the 17 percent increase in impervious surfaces. Pervious surfaces declined by 27 percent. The majority of the increase in urbanized landscapes has been in San Jose and the urban areas around the Bay, the area east of the Oakland Hills, and northern Bay cities including the Sonoma and Napa Valleys. While the increase in tree cover in urbanizing areas is a positive development, the overall increase in impervious surfaces has negative implications for water quality.

Part II. Value of Current Benefits

The value of annual benefits produced by the current tree canopy was determined based on current (2002) urban tree canopy extent for the urbanized portion of the study area. We mapped five climate regions and three tree zones

within the Bay area for six land use classes. Benefits per unit area of canopy cover, based on revision of existing benefit models developed by the Center for Urban Forest Research on a per tree basis, were applied to the measured canopy cover to calculate benefits associated with runoff reduction, property values, air quality, carbon dioxide removal, and building energy use savings. Tree numbers were estimated based on measured canopy cover and tree size determined from earlier studies in Sacramento.

Total annual benefits for the region were $5.1 billion, ranging from $103 million for San Francisco County to $1.535 billion for Santa Clara County. Most benefits were associated with low-density residential land use (70 percent), the least with transportation (<1 percent), with 11, 10, 6 and 3 percent for high-density residential, open space, commercial/industrial and institutional, respectively. Larger counties with sizeable residential populations had the greatest total benefits (e.g. Santa Clara, Contra Costa, Alameda). Total benefits were approximately proportional to urban area, number of trees, and population (the latter is approximately proportional to urban area). However, smaller counties such as Marin can be elevated in the standings due to their relatively dense tree cover.

Property value enhancement accounted for 91 percent of total benefits, followed by energy (electricity and natural gas) at 6 percent, storm runoff (hydrology) at 2 percent, and fractional percentages for air quality and carbon dioxide. Air quality benefits from deposition and avoided pollution were offset to varying degrees by BVOC emissions. In Alameda County the value of BVOC emissions were greater than the savings resulting from deposition and avoided pollution, resulting in a negative value for San Francisco or Berkeley.

III. Value of Future Benefits

The value of future benefits from tree canopy depends on projections of future canopy cover, which depends primarily on future tree planting and survival rates (e.g. quality of nursery stock, planting depth, level of tree care). Canopy cover also varies with land use, so land use changes driven by urban growth and development will also influence future canopy cover. In this analysis, canopy cover increases of 1.5, 3, 6, and 9 percent were used to illustrate effects of various levels of canopy cover change. Since land use projections were not available for the Bay area, it was assumed that land use changes occurred within current urbanized boundaries and were reflected in conversion of pervious cover type to either impervious or canopy cover.

Tree number increases ranged from 2 to 13 million, or 5 to 31 percent. “Canopy cover increase” in this context refers to actual canopy cover and not it’s relative change, i.e., a 3-percent canopy cover increase from 29 to 32 percent represents a change in canopy cover (and tree numbers) of approximately 10 percent. Benefits increased approximately in proportion to the change in tree numbers. Increased canopy cover resulted in added benefits ranging from

$237 million (4.6 percent) to $1.424 billion (27.5 percent), and total benefits for all trees ranged from $5.2 to $6.6 billion.

A more detailed analysis was conducted based on a planting goal of a 3-percent canopy cover increase. The projected increase of 4.3 million trees resulted in added benefits of $475 million, or $69 per capita. Increases in tree cover were distributed in proportion to existing tree numbers, so that counties like Santa Clara and Contra Costa experienced the largest increases. Per capita benefits tended to be higher where urban areas were less densely populated, e.g., Marin and Napa counties.

Recommendations

The information provided in this report on the projected benefits of a substantial tree planting program in the San Francisco Bay area is a valuable asset for the region and its residents and should be widely disseminated. Existing tree canopy cover is a valuable commodity that needs to be preserved and protected, and informing residents of the Bay area of the ecosystem services and provided by their trees is a good first step to protecting and strengthening the urban forest.

This study is a starting point for many possible ventures to support the Bay area's urban forest. This report concludes with a number of suggestions for the future, including ideas for private/public cooperation, future research, potential advances in technology, and opportunities for collaboration.

The San Francisco Bay area is a vibrant region that will continue to grow. As it grows it should also continue to invest in its tree canopy. This is no easy task, given financial constraints and trends toward higher density development that may put space for trees at a premium. The challenge ahead is to better integrate the green infrastructure with the gray infrastructure by increasing tree planting, providing adequate space for trees, adopting realistic tree canopy cover targets, and developing strategies, plans, programs, and municipal assessments to maximize net benefits over the long term, thereby perpetuating a resource that is both functional and sustainable. The Center for Urban Forest Research looks forward to working with the Bay area's municipalities and many professionals to meet that challenge in the years ahead.

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Introduction

As increasing population drives urban growth, impervious surfaces increase the flow of contaminants into water bodies, air pollution increases from commuting traffic, and more energy is required to support new development. The urban forest works to mitigate these adverse effects associated with the built environment.

- Impervious surfaces increase runoff during storm events. Urban trees retain rainfall on their leaf surfaces and reduce storm water runoff.
- The built environment absorbs and stores solar radiation, causing urban heat islands that accelerate ozone formation and increase the need for air conditioning. Urban tree canopy cover can play a significant role by reducing the heat island effect through shading and evapotranspirational cooling of the air.
- City trees absorb air pollutants and sequester atmospheric carbon dioxide. By shading parked cars and asphalt concrete streets, trees reduce the release of evaporative hydrocarbons that are involved in ozone formation.
- Tree shade and air temperature reductions reduce the rate that street surfaces deteriorate and decrease repaving costs.
- Additionally, urban trees increase property values.

Although the benefit of any single tree may be small, the sum of benefits is significant when it comes to mitigating the environmental impacts that result from converting natural land cover to built environments.

The nine-county San Francisco Bay area is experiencing rapid growth, especially in outlying areas, which is accelerating air pollution, water, and energy demand problems. These problems urgently need solutions. Urban forestry is integral to land use planning, mitigating water shortages, conserving energy, improving air quality, enhancing public health programs, increasing land values and local tax bases, providing job training and employment opportunities, reducing costs of city services, and increasing public safety. The goal of this study by the Center for Urban Forest Research is to describe the structure of the region's urban forest and quantify the value of the ecosystem services it produces. This information will enhance our understanding of the relevance of urban forests and extent to which they impact the environmental and economic health of Bay Area communities and the potential return on investment in planning and management.

Study Area

The study area is located in the San Francisco Bay area of California, USA, which includes over 200 municipalities and is home to approximately

6.7 million people (Fig. 1). The nine counties that surround the bay, San Francisco, Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, and San Mateo (Fig. 2), have an area of 18,000 km^2. The region consists of rangeland, agricultural fields, urban and peri-urban environments, and forests along the coast and western side of the bay. It also includes such unique features as salt ponds, mudflats, saltwater wetlands, and vernal pools.

The study area consists of the urbanized portion of this nine-county region. The light gray color in the Landsat 7 image from 6 September 2002 (Fig. 3) indicates the built environment. The majority of the urban environment surrounds the San Francisco Bay, with a secondary area of development east of the Oakland Hills including Pleasanton and Walnut Creek, and a string of cities in valleys north of the bay, such as the Sonoma and Napa Valleys.

The actual study area for this project excludes a small portion of the nine-county area because the Landsat path 44 does not include the northwest corner of Sonoma County (Fig. 3). As a result, six cities are excluded from the analysis. Cloverdale, with a population of 6,800 people, is the largest city excluded.

From 1980 to 2000, the population in the nine counties increased by 30%, from 5.1 million to 6.7 million people (ABAG 2003). There are over 200 cities within this region ranging in size from less than 1,000 to over 900,000. San Jose (900,000), San Francisco (775,000), and Oakland (412,000) are the largest cities in the area. All the cities surrounding the Bay form a large, continuous, urbanized area.

Population growth since 2000 has occurred primarily on former farmland on the region's edge, with at least 165,000 workers now commuting to the Bay area each day (King 2005). Cities experiencing relatively rapid growth include Brentwood, whose population has nearly doubled to 41,000 in the past four years, Dublin, Fairfield, and Santa Rosa.

Definitions

Tree and shrub canopy cover are subsequently referred to collectively as tree canopy cover or simply canopy cover. Trees are not easily distinguished from shrubs with remotely sensed data without multiple, high-resolution data sets and a sophisticated level of analysis (Baltsavias et al. 2007) not feasible for this study.

Land cover for any particular cover type can be expressed on either an area or percentage basis. For example, tree canopy cover (TCC) can refer to either tree canopy cover area (TCCA) or tree canopy cover percent (TCCP). TCCA is defined as area of ground surface covered by all trees and shrubs within a site and is calculated as the sum of the crown projection areas (CPA) of all trees and shrubs on the site, where CPA is the area of ground covered by the vertical projection of the outermost perimeter of the natural spread of foliage. Small openings within the outermost canopy perimeter are included.

Fig. 1—Location of the nine-county San Francisco Bay study area (USGS 2003, CaSIL 2004)

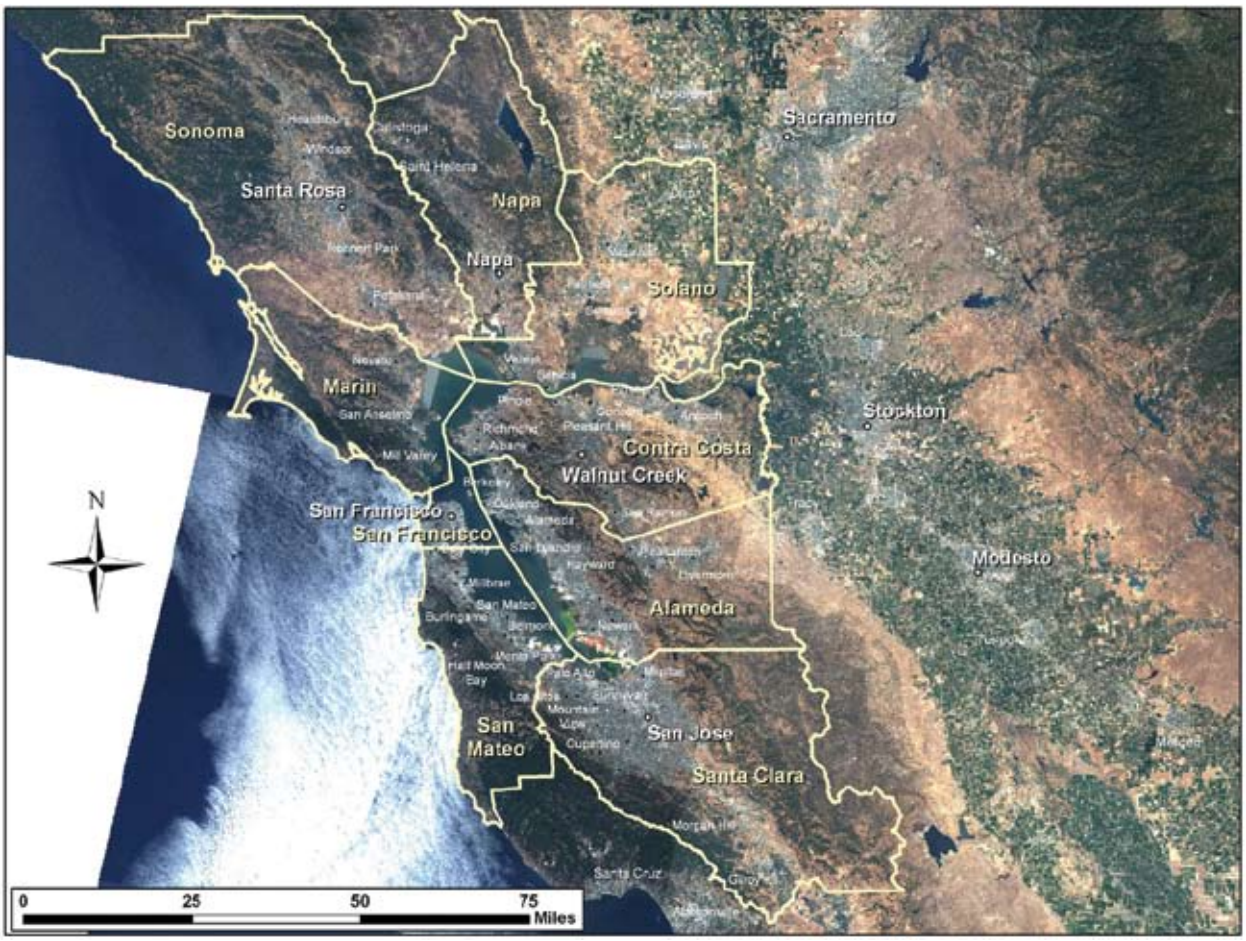

Fig. 2—Location of nine counties and major cities in the San Francisco Bay area (CaSIL 2004)

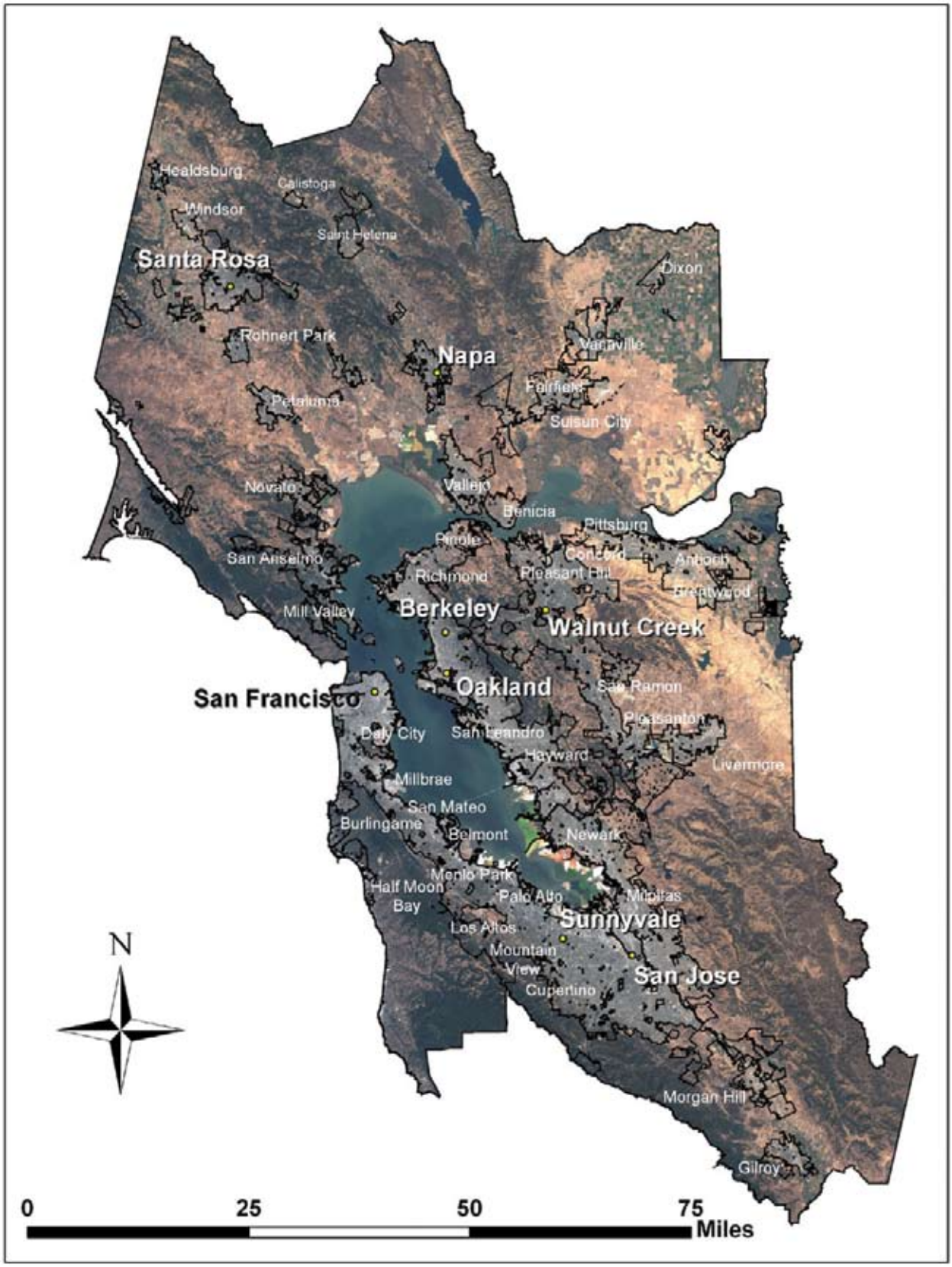

Fig. 3—The San Francisco Bay nine-county study region. The light gray color indicates the urbanized areas

TCCP is TCCA divided by total ground area for the site and is expressed as a percentage. Other cover types, e.g. pervious and impervious surface, are simply the area of each, or the area of each divided by total ground area if given as a percentage.

In the analysis that follows, total land area refers to urbanized portions of the study area only (Fig. 3), unless otherwise indicated. Urban areas and urban clusters are as defined for the 2000 Census: densely settled regions containing at least 50,000 people or 2,500 to 49,999 people, respectively (U.S. Census 2002). Portions of a few incorporated places that contained a significant amount of sparsely settled territory are excluded. An urban cluster generally consists of a geographic core of block groups or blocks that have a population density of at least 1,000 people per square mile, and adjacent block groups and blocks with at least 500 people per square mile.

Report Sections

Results are presented in three sections:

I. Historic canopy cover change. Canopy cover for urban areas of the nine-county region (except northern Sonoma Co.) was mapped based on Thematic Mapper (TM) data for 1984, 1995, and 2002. Changes in impervious (rooftops, paving) and pervious (turf, bare soil) land cover for these periods are also given.

II. The value of annual benefits produced by the current tree canopy. Benefits are tabulated for urban areas of each county using 2002 TM imagery. Five of nine counties are further subdivided into two parts based on climate to derive estimates of resource units (e.g., kWh of electricity saved, tons of ozone uptake). To translate tree benefits into financial terms, the study area is divided into five climate regions (CEC 2006) and three tree zones that correspond to our reference city data collected in San Francisco, Berkeley, and Modesto. Results are stratified by land use (residential, commercial/industrial, institutional, transportation and open space/other).

III. The value of future tree canopy. Canopy cover was determined for tree cover increases of 1.5, 3, 6 and 9 percent. The value of future benefits for those levels of cover was calculated. More indepth analysis was made for a targeted increase in canopy cover of 3 percent.

I. Canopy Cover Change 1984–2002

Introduction

Remote sensing provides an efficient method for characterizing changes in the ecosystem as it is converted from a natural to a built environment. It allows for the measurement of the size, distribution, and composition of the urban ecosystem and its changes over time.

Objects in urban environments have a characteristic scale of 10–20 m (Small 2003). At a spatial resolution of 30 m, satellite imagery is not able to consistently measure single objects. Initial remote-sensing studies of urban land cover used traditional hard classifiers, which assume a single class for each pixel. These classification techniques are not statistically valid in an urban environment where the majority of the pixels are a combination or mixture of classes.

Instead of assigning each pixel within the urban environment a land use type, Ridd (1995) characterized the urban ecosystem with the vegetation-impervious surface-soil (V-I-S) model. In this model, the urban environment is defined as a combination of green vegetation, impervious surface, and soil. Water surfaces are ignored or masked out of the analysis.

Since urban environments are characterized by objects that are smaller than the spatial resolution of Landsat Thematic Mapper, the pixels are spectrally a mixture of the different objects covered by the pixel. To characterize the urban environment, sub-pixel estimates of urban land cover are needed. Spectral mixture analysis (SMA) has been very successful in studying urban environments. SMA gives a sub-pixel estimate of each land cover defined by an endmember. Endmembers define the spectrally pure instance of each land cover. Variations in SMA have been used to characterize a variety of urban environments (Phinn et al. 2002; Wu and Murray 2003; Small 2005).

Phinn et al. (2002) found linear SMA to be the most accurate method for determining the V-I-S model with moderate-resolution satellite imagery. SMA has the advantage that each fraction is based on a physical and measurable quantity. Other transformation techniques such as Kauth-Thompson provide estimates of greenness, brightness, and wetness but are not directly tied to physically quantifiable materials such as vegetation, impervious surface, and soil (Small 2005).

The standard SMA model for urban classification uses four endmembers: vegetation, soil or nonphotosynthetic vegetation (NPV), impervious surfaces, and shade (Wu and Murray 2003; Wu 2004). The shade component of the model is problematic. The shade component in an urban environment measures actual shade caused by nearby buildings or water or a darker example of an endmember. Because of the shade component in the analysis, the endmembers

chosen for vegetation, NPV, and impervious surfaces are bright examples of these surfaces. The actual sub-pixel area covered by one of these three physical endmembers is some combination of vegetation, NPV, or impervious surface plus the shade component. For example, if concrete were used as the impervious endmember then asphalt would be represented in this model as a combination of impervious surface and shade. The shade component is not actual shade but instead only measures how much darker the asphalt is than the concrete. In this example, part of the asphalt is misclassified as shade.

Although the shade component is problematic, it does contain important information that can be used to discriminate between irrigated grass and canopy cover. Roberts et al. (1999) used the shade and vegetation component to discriminate between agricultural fields and canopy cover in the Amazon rain forest. Since trees and shrubs shade themselves, canopy cover is characterized by a combination of vegetation and shade. Irrigated lawns and golf course fairways do not shade themselves and are therefore described by only a vegetation fraction.

Different approaches have been used to minimize the problem with shade. Wu and Murray (2003) estimated impervious surfaces by combining the impervious surface fraction with the shade fraction to determine the overall impervious surface fraction. Wu (2004) found that this technique worked for fully urbanized environments but did not perform well in residential areas or at the wildland-urban interface. He suggested the use of a normalized SMA (nSMA) where brightness variations were reduced by using the mean value for all the bands. This preserved the shape of the spectral curve between the different endmembers but minimized the brightness variations. With the nSMA model, only three endmembers are used and shade is removed. This model produced better results over a wider range of urban and peri-urban environments.

Small (2002, 2004) used a different approach, a three-endmember SMA model of vegetation, bright albedo, and dark albedo. He showed that the urban environment can be distinguished from natural environments with this model. The defining characteristic of the urban environment is its spectral mixture. The majority of urban pixels are mixed and not pure examples of a specific land cover.

Methods

We measured historic canopy cover and historic impervious surface extents and their changes over time with Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) imagery from 1984, 1995, and 2002 (Table 1). The dates of the satellite imagery are nearly the same for each year and the solar elevation and angle are closely matched between the Thematic Mapper images. This produces shading conditions within the images that are comparable.

In order to produce reliable results, the satellite imagery was orthorecti-

Table 1—Satellite imagery

Imagery	Date	Resolution (m)	Ortho accuracy (m)
TM	September 7, 1984	30	10.3
TM	September 6, 1995	30	10.3
ETM+	September 1, 2002	30	7.5
Aerial photography	October 1, 2002	0.6	6.2

fied and radiometrically calibrated. Aerial photography used for orthorectification and accuracy assessment was taken only a month after the ETM+ imagery (USGS 2004). This reduces temporal decorrelation between the 2002 ETM+ data and the aerial photography. This is especially important since certain areas were being developed during the 1-month period between when the satellite imagery and aerial photography were taken.

Orthorectification converts satellite imagery to a map (Jensen 1996). The process includes georeferencing an image to a map coordinate system and adjusting for parallax distortions caused by elevation changes. The ETM+ 2002 image was orthorectified to high-resolution natural-color orthorectified aerial photography. The 1984 and 1995 TM images were orthorectified to the 2002 ETM+ image. The standard orthorectification accuracy for TM and ETM+ imagery is 15 m. We were able to achieve an accuracy of 7.5 m for the 2002 image and 10.3 m accuracy for the 1995 and 1984 images. One hundred and thirty points were sampled from throughout the area for the orthorectification. For a discussion of orthorectification accuracy, see the ERDAS Field Guide (ERDAS 2002).

Radiometric calibration corrects imagery for differences in sensor calibration and atmospheric conditions. The imagery was acquired during clear sky conditions but the calibration of the sensor drifts. The 2002 ETM+ imagery was converted to exoatmospheric reflectance based on published post-launch calibration coefficients (USGS 2005). Objects within the image that are considered radiometrically stable, such as deep lakes, were chosen as pseudo-invariant (PIV) image endmembers. Golf course fairways, flat rangeland, and building rooftops were also used as PIVs. The 1995 and 1984 images were radiometrically calibrated with linear regression to the 2002 ETM+ image using the PIVs with an $R^2 = 0.99$.

Preliminary investigation of the imagery began with a minimum noise fraction transformation (MNF). An MNF transformation is a cascading form of principle component analysis. The MNF transformation orients the axes to include the signal-to-noise ratio for each of the bands. The statistics for the signal-to-noise ratio are derived from the imagery within a user-defined homogeneous area. By looking at the scatter plots for the first three components of the MNF, the overall shape of the spectral mixing space within the imagery was determined (Fig. 4). The scatter plots are a two-dimensional projection of a three-dimensional cloud of points that defines the feature space. The color

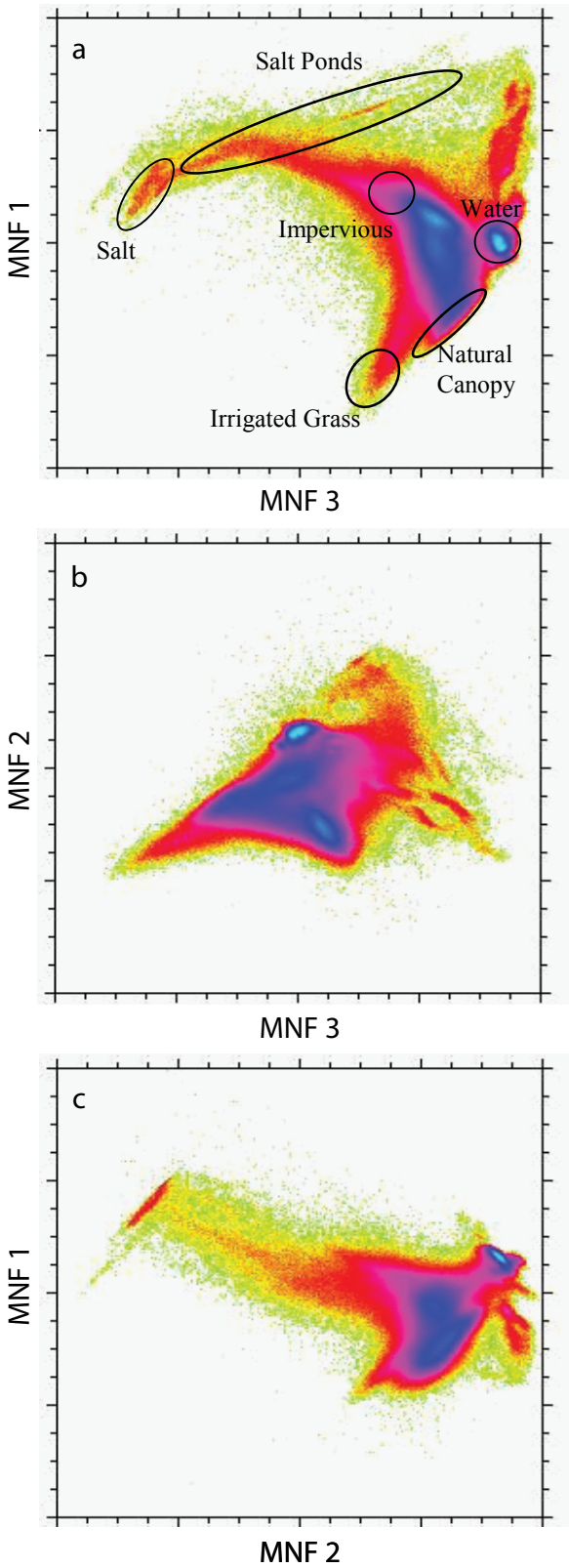

Fig. 4—Scatter plots between the first three components of the MNF for the entire nine county study area. *a* MNF1 vs 3. *b* MNF 2 vs 3. *c* MNF 1 vs 2

represents the point density. Yellow and green are the lowest point densities. Blue and cyan represent the highest density.

Figure 4a–c shows three alternate views of the same cloud of points. The regions at the edge or corners of the scatter are pure pixels of one land cover. The majority of the pixels are mixed and in the middle of the scatter plot. In order to describe an area with linear mixture modeling, it needs to have a triangular appearance with concave edges. When both the natural and urban environments are considered together, a three- or four-endmember linear mixture model is not adequate.

An MNF transformation was also conducted on only the urban areas. Figure 5 illustrates how the feature space becomes less complex when the area is restricted to only the urban environment. The feature space collapses to a triangular mixing space with concave edges. The pixels that are at the vertices of the feature space represent pure or unmixed pixels. These pixels are candidates for endmembers used in the SMA. The simplified triangular mixing space of the urban areas shows that it can be modeled by linear spectral mixing with a minimum of three endmembers, although the use of four endmembers is also possible. There is some nonlinear mixing associated with the canopy cover as seen by the slightly convex edge between water or deep shadow and irrigated grass. When MNF 1 is plotted against MNF 2, the NPV endmember becomes obvious.

In this portion of the analysis, we used the V-I-S model but modified the green vegetation component. In an urban environment, green vegetation is composed of trees, shrubs, and irrigated grass. We are interested in the canopy cover from trees and shrubs. We remove the irrigated grass portion from the green vegetation component to form a canopy cover category and add the irrigated grass to soil to form a pervious surface category. Our model of the urban environment changes the vegetation–impervious surface–soil model to a canopy cover–impervious surface–pervious surface model. Land cover under the tree canopy is not characterized.

In order to tease out a canopy cover sub-pixel estimate, we will use a combination of the nSMA variation and Small's SMA model. Impervious surfaces and soil / NPV will be characterized by using the normalized SMA model. The two classifications will be combined to provide an overall canopy cover–impervious surface–pervious surface subpixel estimate for the San Francisco Bay area.

Wu (2004) only tested the accuracy of the nSMA model for Columbus, Ohio, and for only one land cover class: impervious surface. We will test the normalization method on the large and varied environment of the entire San Francisco Bay area and calculate the accuracy for all three land cover components.

The nSMA model transforms the feature space. Using the standard principal component analysis for the urban areas results in a linear mixing space defined by three endmembers: impervious surfaces, NPV / soil, and vegetation (Roberts et al. 1999; Gilabert et al. 2000; ERDAS 2002; Wu 2004). The normalization method removed the shade component from the mixing space. This technique provides a more robust method for estimating the three endmembers throughout the urbanized area.

In order to distinguish canopy cover from irrigated grass within the vegetation fraction, we need to reintroduce the shade component. We followed the model proposed by Small (2002) that urban environments can be defined by three endmembers: vegetation, dark albedo, and bright albedo. This model performs well except in areas where the unmodeled soil/NPV class predominates. The Small SMA model will only be used to discriminate canopy cover from irrigated grass within the vegetation fraction estimated by the normalized SMA method.

Gilabert et al. (2000) modeled reflectance from heterogeneous canopy cover and found that it is not governed by linear mixing. At the landscape scale for homogeneous canopy cover, linear mixing is a feasible approximation. A more detailed spatial analysis of heterogeneous canopy cover highlights the nonlinear mixing and shadowing that occurs

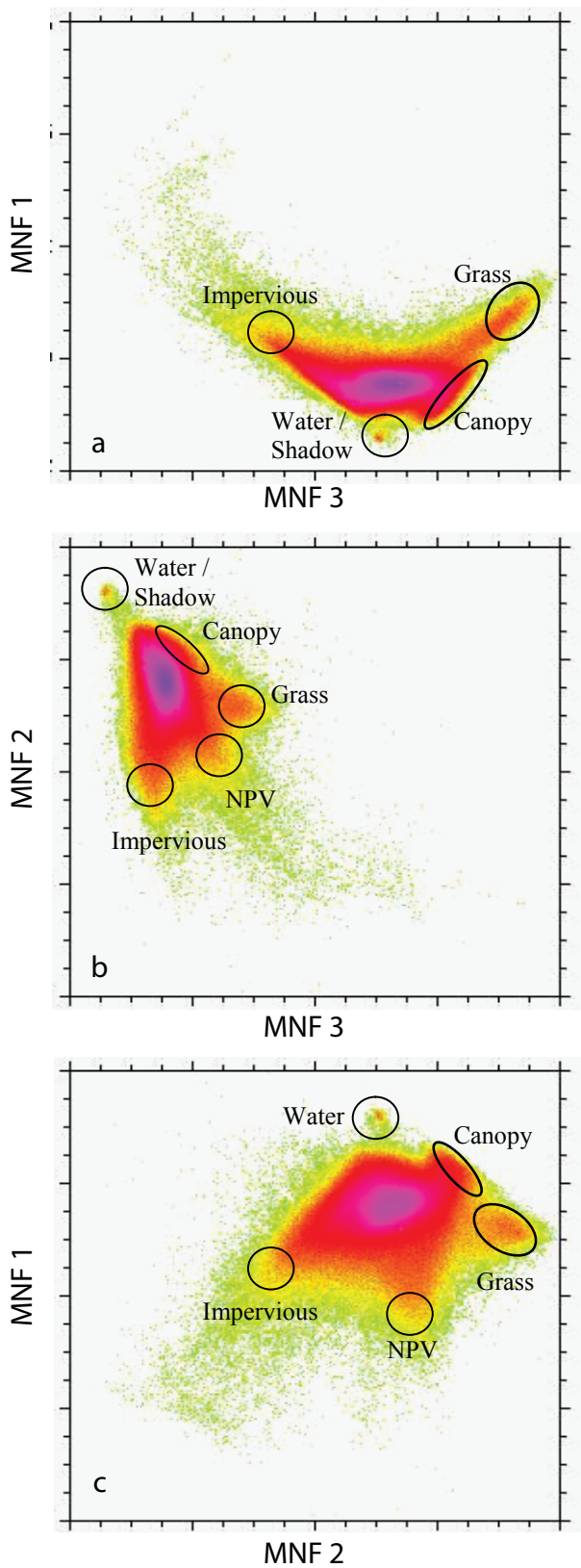

Fig. 5—Scatter plots between the first three components of the MNF restricted to only urban areas. *a* MNF1 vs 3. *b* MNF 2 vs 3. *c* MNF 1 vs 2

within the canopy cover. For trees and shrubs that are dispersed and do not form a closed canopy, vegetation is systematically underestimated. This is caused by the significant shading component associated with dispersed plants. The aerial photography will be used to calibrate and correct for the systematic underestimate of the vegetation component and to assess the accuracy of the overall classification.

A number of areas were masked from the imagery before classification because of spectral confusion. The salt ponds are easily confused with bright impervious surfaces, such as light-colored rooftops. Because water and shade are spectrally similar, water needs to be masked from the imagery before classification. Large areas of grass, such as parks and golf course fairways, that produce spectrally pure pixels of unshaded vegetation were also removed by masks from the imagery. This reduces the confusion between irrigated grass and canopy cover within the vegetation fraction of the classification.

The water mask was constructed from portions of the National Wetlands Inventory and a Spectral Angle Mapper classification of water within each of the three images. Salt ponds and tidal salt marshes change dramatically in their spectral signature within the three Landsat images but do not change in their land cover extent. They were masked out based on the National Wetland Inventory. Open water, reservoirs, lakes, and streams were classified with the Spectral Angle Mapper. These classified areas of water did change in their extent throughout the imagery. The Spectral Angle Mapper performed well in classifying water with large sediment loads in the bay. Shadows caused by the large buildings in downtown San Francisco were confused with water in all classification methods attempted but had the least confusion with the Spectral Angle Mapper. Other shaded urban areas were not classified as water by the Spectral Angle Mapper. The water mask was edited by hand to not include the downtown San Francisco area.

Urban areas have unique irrigated grass regions associated with specific land uses. These areas are large enough to produce spectrally pure regions of unshaded vegetation or grass. Since the imagery is from September, all grass that is not irrigated has turned brown. The only areas of unshaded green vegetation are irrigated grass areas in parks, golf course fairways, and agricultural fields, which were masked out as described above. Areas of irrigated grass were identified with the Spectral Angle Mapper. The classification of the areas was modified by including contextual and texture information. Since the areas of interest produce sharp contrast with the surrounding environment and they form a contiguous conglomeration of pixels, information about the variance of red, near-infrared, and short-wave (TM bands 3, 4, and 5) and a neighborhood function were included in the classification of irrigated grass areas.

The aerial photography was sampled for calibration and accuracy assessment of the land cover classes: trees, impervious surface, and pervious surface. There were a total of 650 points randomly sampled within four different

regions of the study area: San Francisco, San Jose, Walnut Creek/Oakland Hills, and the area surrounding the San Antonio reservoir. Half of these points were used for calibration; the other half for accuracy assessment. Each sampled area was 3 × 3 pixels or 90 × 90 m (Fig. 6). The different land covers were digitized from natural color aerial photography. The sampled area was 90 × 90 m to minimize the effects of errors in the georeferencing (Wu 2004).

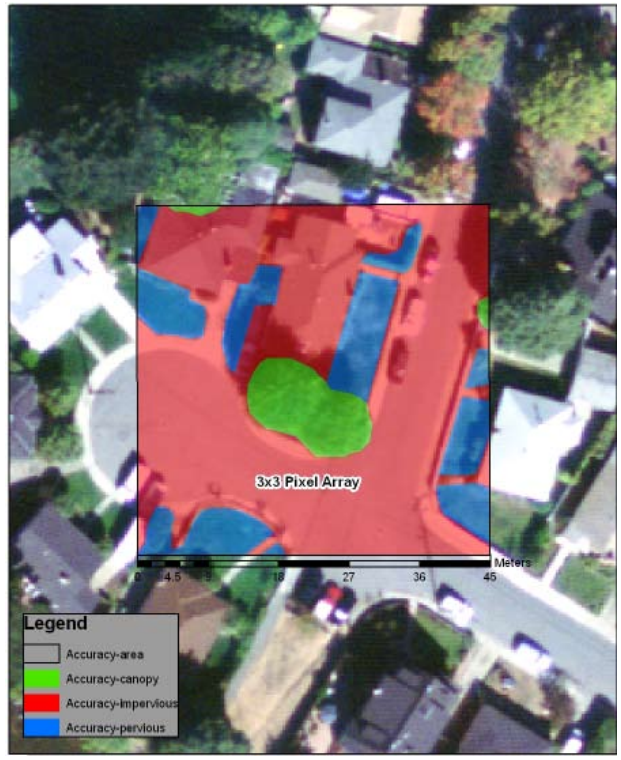

Fig. 6—Example of a 3 x 3 pixel array overlaid on an aerial photo to determine accuracy

Accuracy is measured as root-mean-squared error (RMSE) and systematic error (SE) (Wu 2004). RMSE measures the overall accuracy for each of the 650 samples. SE measures how much the sample overestimates or underestimates the land cover (Table 2).

Using the normalized SMA technique and only measuring impervious surface for Columbus, OH, Wu (2004) had an RMSE of 10.1% with an SE of −3.4%. Wu and Murray (2003), also only measuring impervious surface for Columbus, OH, had an RMSE of 22.2% and an SE of 15.9%. Small (2001) compared vegetation fractions (not canopy cover) from Thematic Mapper imagery with "illuminated vegetation" in high-spatial resolution imagery. He assumed a 10% error for each point and had an R^2 fit of 0.999.

The results of the analysis are presented by urban area as defined in the 2000 Census (U.S. Census 2002). This will show how land cover has changed from 1984 to 2002 for an area that is now considered urban. The overall percentage of canopy cover and impervious surface for each urban area are reported for 1984, 1995, and 2002. The percentage of change in canopy cover and impervious surface for each urban area between 1984 and 2002 is also discussed. Changes in canopy cover and impervious surface per pixel of greater or less than the RMSE and SE associated with each category are also mapped for the study area.

Besides quantifying land cover conversion from a natural to an urban environment for an area that is currently urban, we also analyzed the growth pattern of the urban boundary from 1984 to 2002. Urban extent was calculated from the SMA. Pixels were classified as urban based on an impervious surface percentage greater than 20% within the study area (Lu and Weng 2004). Large grass areas

Table 2—Error associated with TM land cover classification

	RMSE (%)	SE (%)
Canopy cover	13	3
Impervious surface	14	−2
Porous surface	15	−1

such as parks and golf courses that had previously been masked were also added to the area classified as urban.

Results and Discussion

The population increased 30% in the nine-county San Francisco Bay area from 1980 to 2000 (ABAG 2003). During that time, the urban built environment increased 73%, from 1,620 km^2 (625 mi^2) to 2,800 km^2 (1,080 mi^2). The rate of land consumed for urban purposes exceeds the rate of population growth by a factor of 2.4, an indication of urban sprawl. Overall urban area increased to 14% from 8% of the total land cover. This conversion of land cover is associated with an increase in impervious surfaces and canopy cover since urban areas have more trees than the surrounding natural area.

Using the current urban area boundaries as defined by the 2000 Census for analysis, we studied how land cover has changed with urbanization from 1984 to 2002. Canopy cover has increased within this area by 10% and impervious surfaces have increased by 17% (Table 3). Urban expansion has been primarily into rangeland and agricultural areas. This has had the effect of increasing canopy cover, but the increase in canopy cover has not kept pace with the increase in impervious surfaces. The increase in impervious surfaces between 1984 and 1995 was almost double that of canopy cover, which has negative implications for stormwater runoff and water quality.

Figures 7–9 show the spatial distribution of canopy for each urban area for 1984, 1995, and 2002. The change in canopy cover from 1984 to 2002 is shown in Fig. 10. Figures 11–13 show the spatial distribution of impervious surface for each urban area for 1984, 1995, and 2002. The change in impervious surface from 1984 to 2002 is shown in Fig. 14.

The established urban areas of San Francisco and Oakland did not greatly change during this 20-year period. The majority of the increase has been in San Jose and the urban areas around the Bay, the area east of the Oakland Hills, and the cities north of the Bay including the Sonoma and Napa Valleys.

Table 3— Land cover conversion (percent) within current urban area boundaries

	1984	1995	2002	Per-pixel RMSE
Canopy cover	19	25	29	13
Impervious surface	39	50	56	14
Pervious surface	42	25	15	15

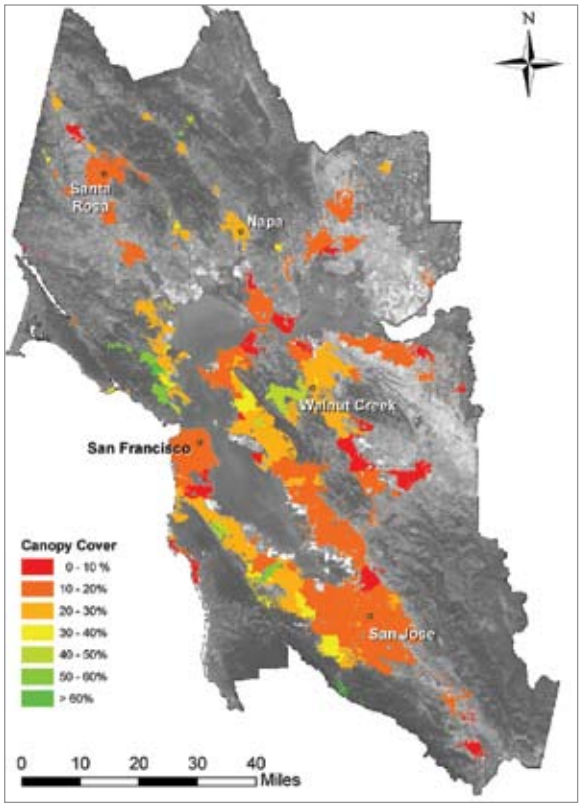

Fig. 7—1984 canopy cover percentage for each of the urban areas within the study area

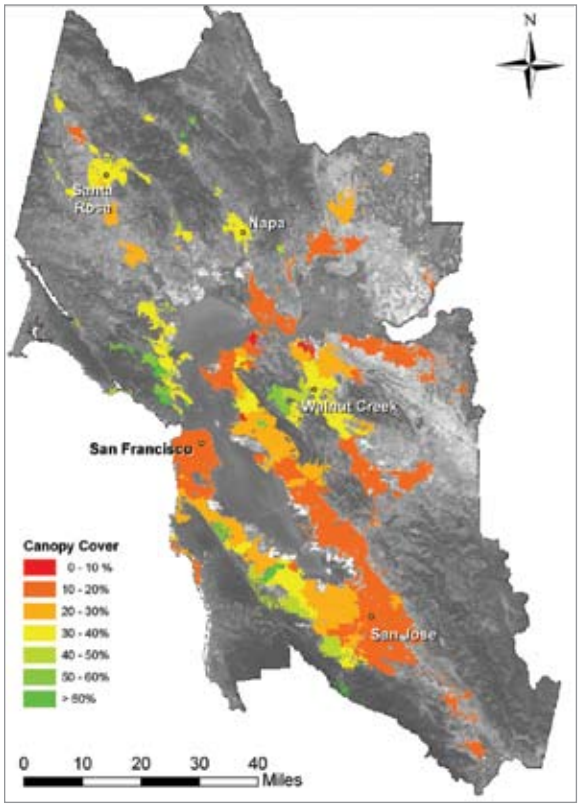

Fig. 8—1995 canopy cover percentage for each of the urban areas within the study area

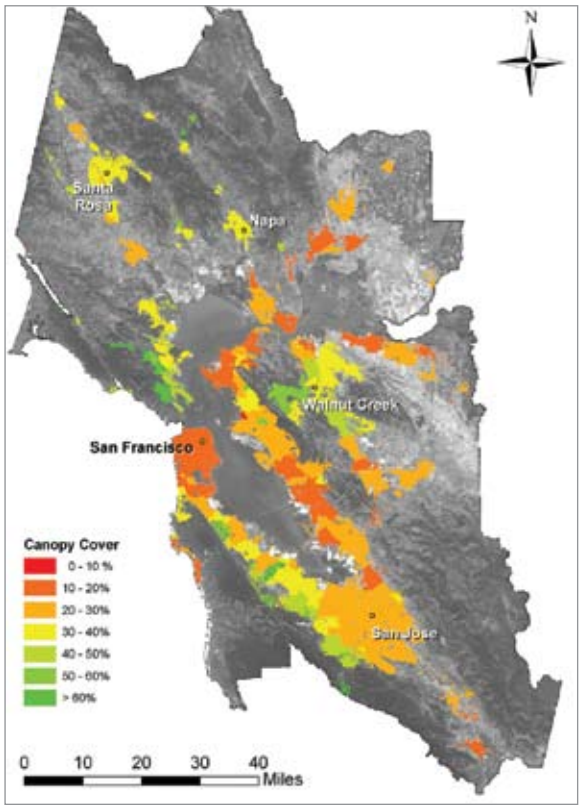

Fig. 9—2002 canopy cover percentage for each of the urban areas within the study area

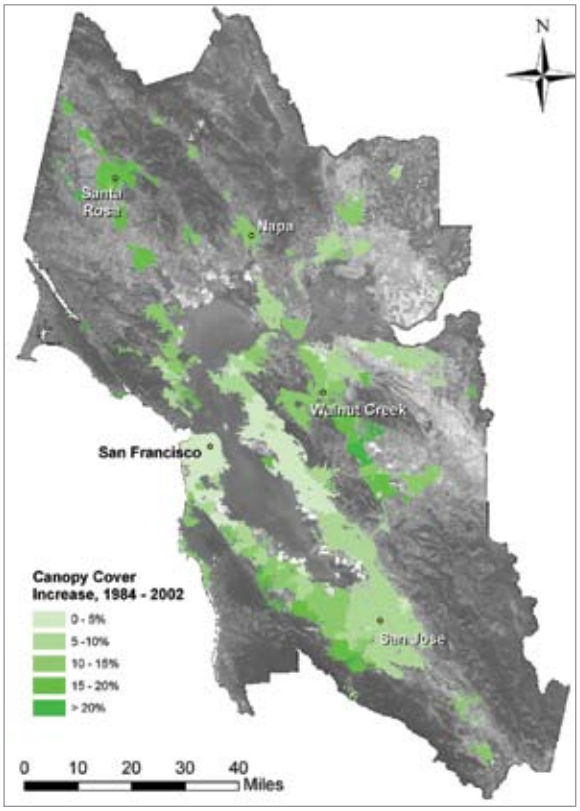

Fig. 10—Canopy cover increase (in percent) from 1984 to 2002 for the urbanized area

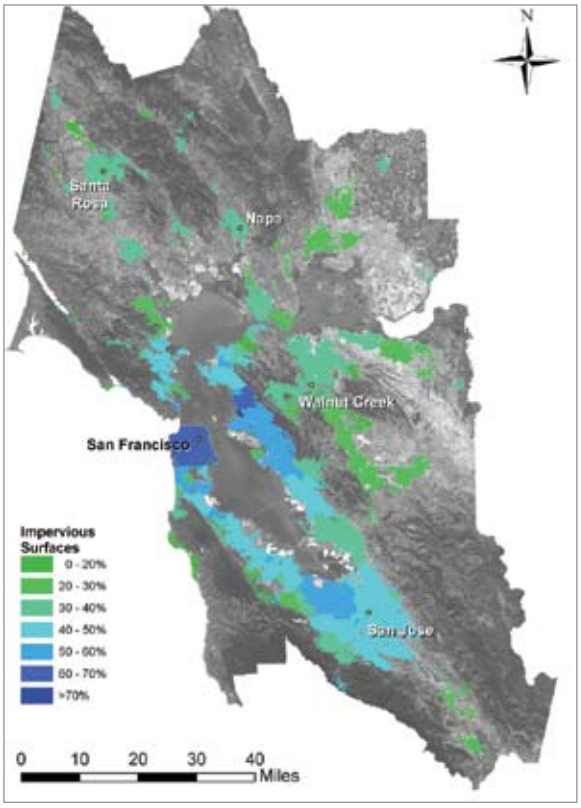

Fig. 11—1984 impervious surface percentage for each of the urban areas within the study area

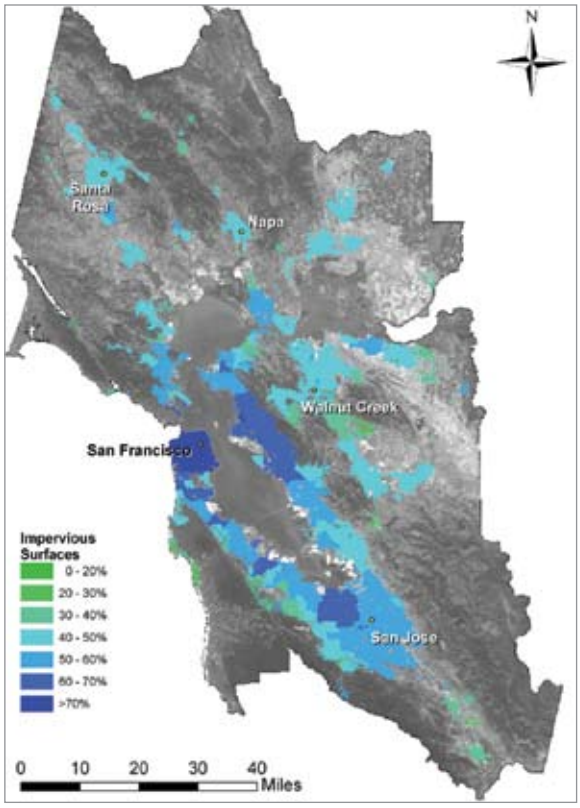

Fig. 12—1995 impervious surface percentage for each of the urban areas within the study area

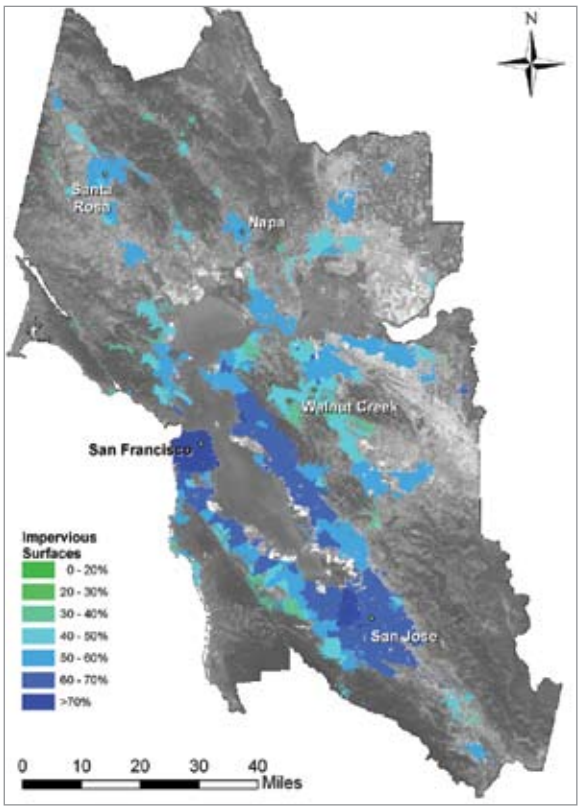

Fig. 13—2002 impervious surface percentage for each of the urban areas within the study area

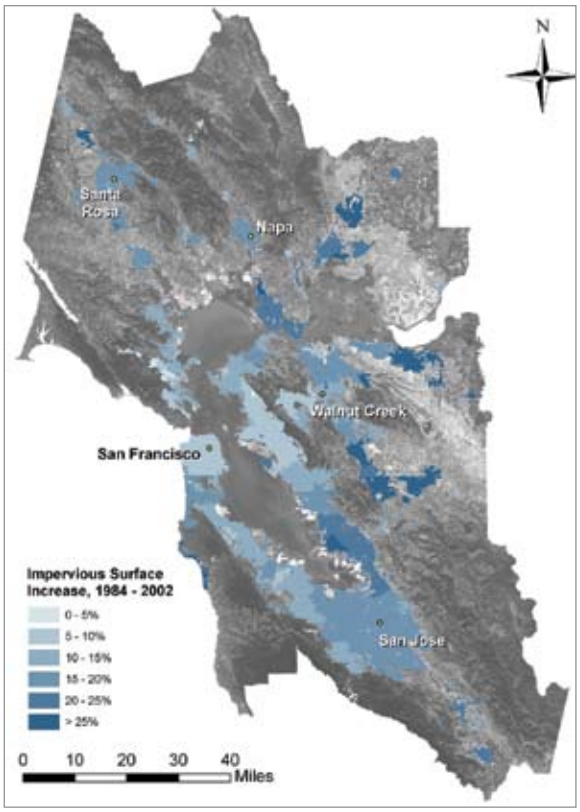

Fig. 14—Impervious surface increase (in percent) from 1984 to 2002 for the urbanized area

The previous figures described how land cover has changed within areas that are currently urbanized. We also studied the pattern and change of overall urban extent for the 1984, 1995, and 2002 time periods. Figure 15 shows the change in urban extent. Urban expansion is primarily around cities not bordering the Bay. This includes cities such as Santa Rosa, Fairfield, Pleasanton, Livermore, the Delta Region near Antioch, and Morgan Hill. There has also been expansion south of San Jose but the majority of urban increase near San Jose appears to be from infill.

The SMA method for determination of urban extent was compared with a classification by the California Department of Forestry (CAL FIRE) for the San Francisco Bay region and with preliminary findings from the U.S. Geological Survey's (USGS) National Land Cover Dataset (Figs. 16 and 17; CAL FIRE 2002). The CAL FIRE urban extent is larger than the SMA urban extent (Fig. 16). The CAL FIRE urban extent is not limited to the 2000 Census urbanized area boundaries, but also classifies

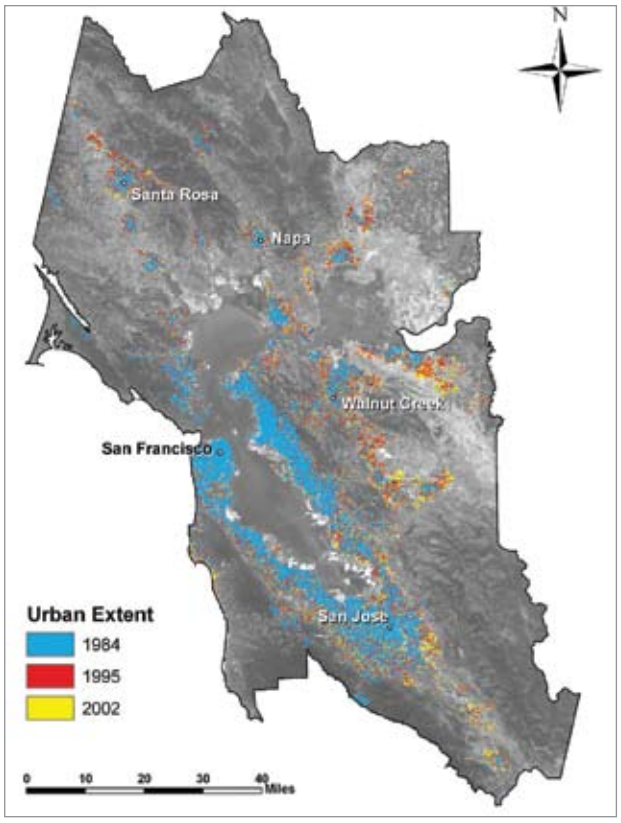

Fig. 15—Urban extent for 1984, 1995, and 2002 from SMA urban classification

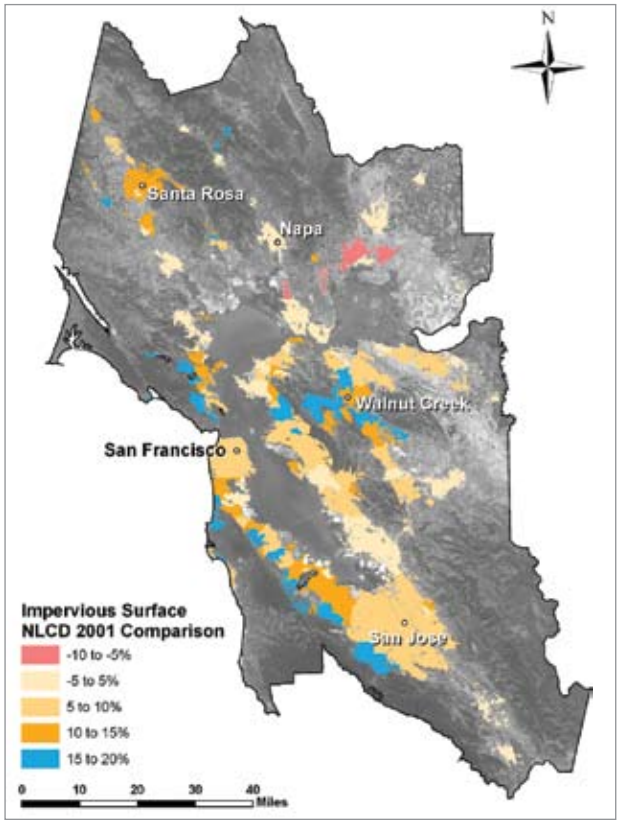

Fig. 16—Comparison of urban extent from the SMA and CAL FIREs 2002 urban classifications

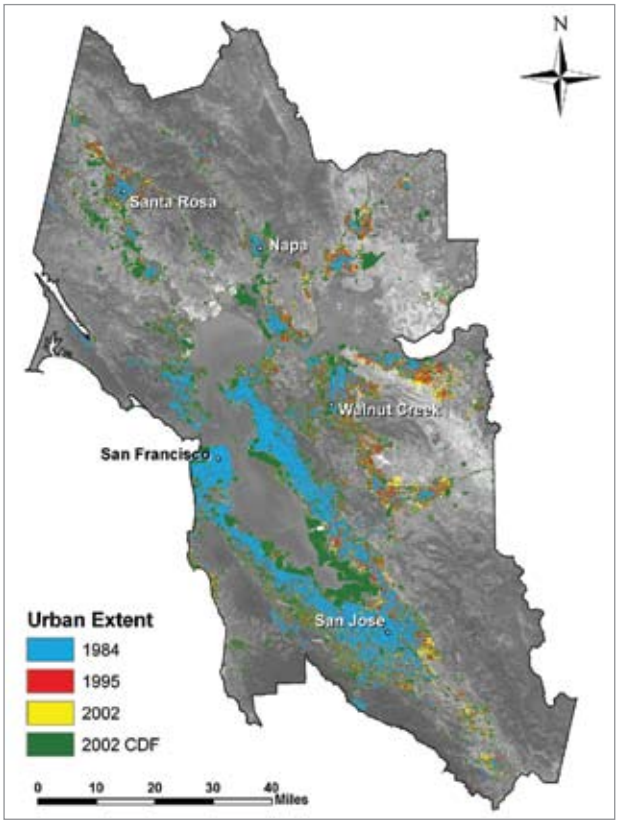

Fig. 17—Comparison of impervious surface from the SMA and the 2001 NLCD by urbanized area

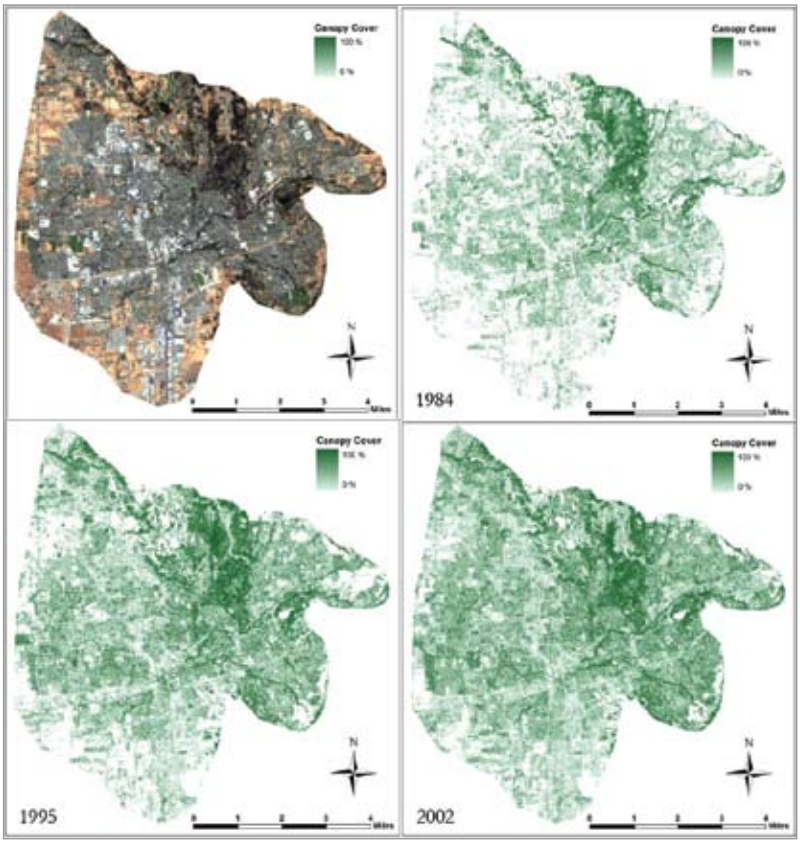

Fig. 18—An example of increasing canopy cover with urbanization. The only area where canopy cover decreases is in the north section of town that expands into a forested area in 2002. The *top left frame* is the natural color satellite image of Santa Rosa in 2002

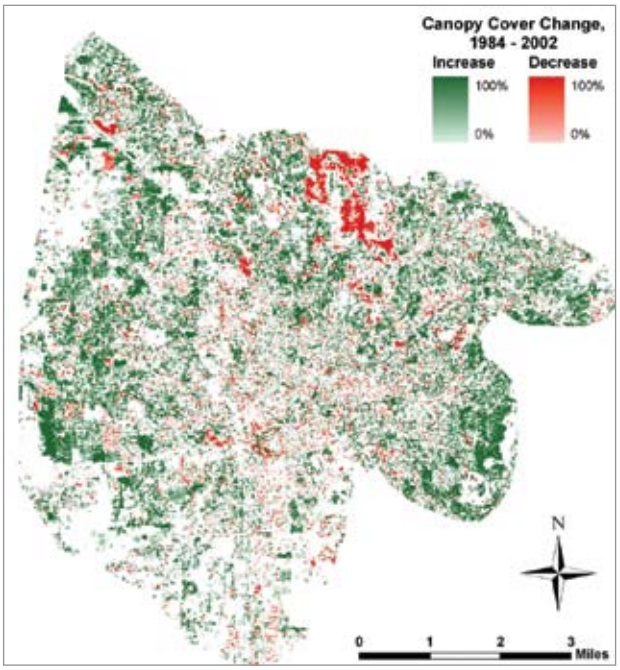

Fig. 19—The change in canopy cover that is greater than or less than the associated per-pixel error for canopy cover from 1984 to 2002 in Santa Rosa

the wetland surrounding the San Francisco Bay as urban. There are also several examples of agricultural fields and brightly illuminated forest areas that are classified as urban areas. The SMA urban classification may underestimate urban extent, but the CAL FIRE urban classification likely overestimates urban extent.

The USGS has also released their preliminary findings of impervious surface extent for the Bay Area as part of the National Land Cover Dataset (NLCD) 2001 (MRLC 2005). Most areas agree within 10% of our impervious surface. Figure 17 shows the SMA impervious surface minus the NLCD 2001 impervious surface. The SMA impervious surface measures a higher impervious surface fraction near forested areas and a lower fraction in agricultural areas than the NLCD 2001 impervious surface. The areas of disagreement are found in areas of greater forest cover at the wildland-urban interface. The USGS has not yet determined the error associated with the NLCD 2001 dataset.

Santa Rosa provides a good example of what is happening throughout the San Francisco Bay area (Figs. 18–21). The majority of change is caused by an increase in urban area surrounding the core of the city. The expansion is primarily into rangeland and agricultural land. There was some loss of canopy cover when the urban area expanded between 1995 and 2002 into a forested area in the north part of town (Figs. 18d and 19). The change in canopy cover that is greater or less than the RMS and systematic error for canopy cover is shown in Fig. 19. The majority of the urban expansion of Santa Rosa occurred between 1984 and 1995 with the increase in impervious surfaces into areas that were formerly agricul-

tural (Fig. 20). Figure 21 shows the change in impervious surface that is greater than the RMS and SE from 1984 to 2002.

There are other processes that changed land cover during this 20-year period besides urban expansion. Canopy cover increases within established urban areas as trees are added and grow larger. Canopy cover is also removed by fire, disease and tree mortality. The Tunnel Fire in 1991 in the Oakland Hills provides an example of this (Fig. 22). The green areas in the figure are vegetation and tree canopy cover, tan is exposed ground, blue and gray are impervious surfaces, and the black near the center of the images is a body of water. The time composite window (bottom right) color codes how the canopy cover changed through this time period. Red is an overall decrease in canopy cover, the magenta shows areas where canopy has been fully restored since the fire, and gray and black are areas where the vegetation has not changed. The black area in the time composite corresponds to a road that passes through the center of the image. The areas of magenta, where vegetation has completely returned, correspond with naturally occurring vegetation on slopes within the burn. The red areas, where the vegetation has not completely returned, are associated with residential areas.

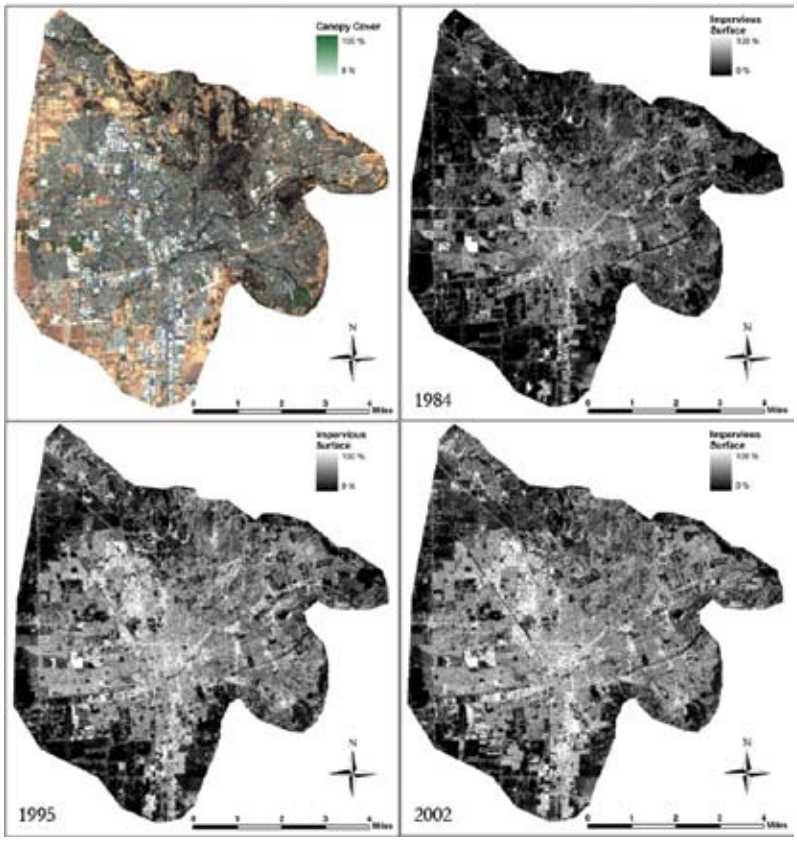

Fig. 20—An example of increasing impervious surface with urbanization. *Upper left* is the natural color satellite image of Santa Rosa in 2002

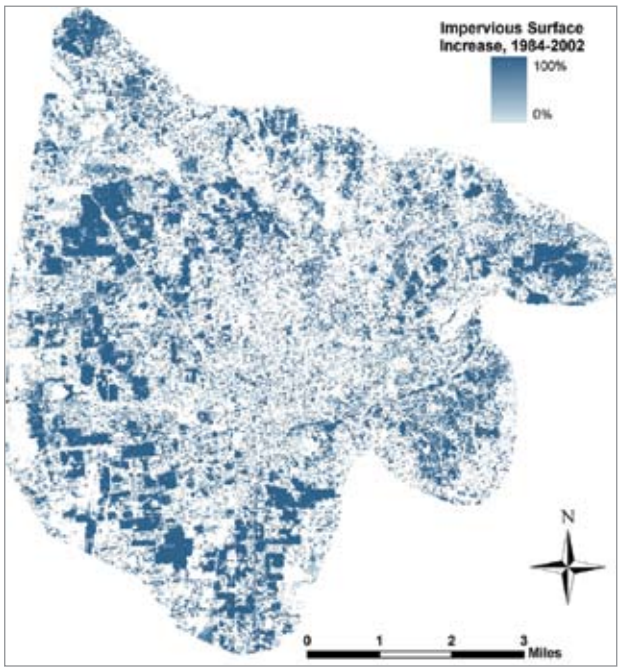

Fig. 21—The increase in impervious surface that is greater than the associated per-pixel error for impervious surface from 1984 to 2002 in Santa Rosa

Conclusions

The urban environment in the San Francisco Bay area has rapidly expanded into what was once predominately rangeland and agricultural areas. A population increase of 30% has driven a 73% increase in urban area. The increase in urban area is associated with increased canopy cover, but this 10% increase has not kept pace with the 17%

increase in impervious surfaces. This was especially true between 1984 and 1995 when impervious surfaces increased nearly twice as much as canopy cover. With the exception of San Jose, the pattern of urban growth or increase in urban extent has been in areas outside the immediate vicinity of the San Francisco Bay.

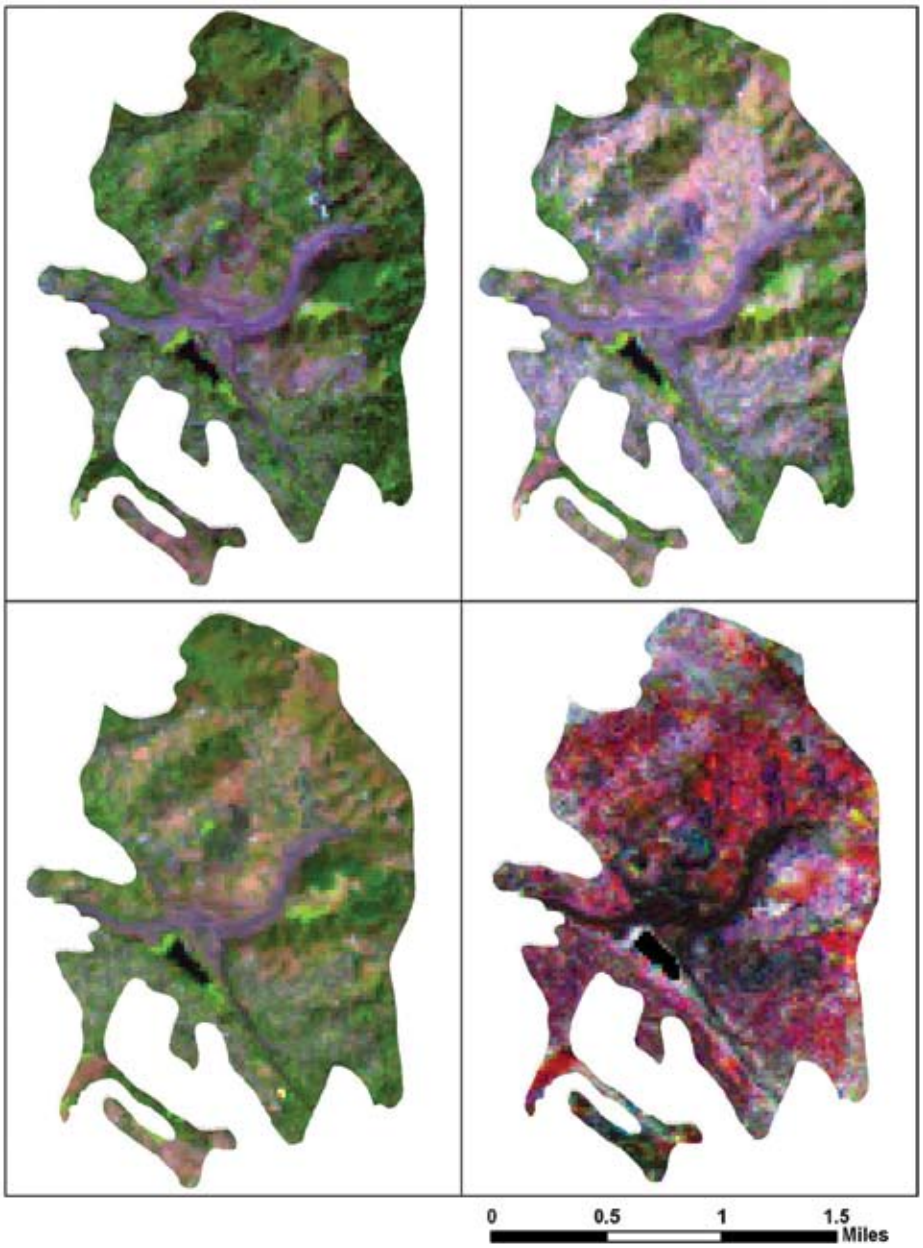

Fig. 22—Changes in land cover from the Tunnel fire in 1991 in the Oakland Hills. The green areas are vegetation, tan is exposed ground, blue and gray are impervious surfaces, and the black is a body of water. The time composite window (*bottom right*) color codes how the canopy cover changed through this time period. Red is an overall decrease in canopy cover (generally associated with residential areas) and the magenta shows areas where canopy has been fully restored since the fire, corresponding to naturally occurring vegetation on slopes. The gray and black are areas where the vegetation has not changed

II. Value of Current Benefits

Introduction

A benefit-cost analysis was conducted for the current (2002) urban tree canopy for the urbanized portion of the nine-county San Francisco Bay area based on the analysis in the previous section. In order to calculate benefits of the urban forest canopy, we mapped five climate regions and three tree zones within the Bay area, determined six land use classes, and converted previous benefit models from a per-tree to a per-unit canopy cover area. Benefits per unit area of canopy cover, based on existing models developed by the Center for Urban Forest Research, are applied to the measured canopy cover to calculate benefits (runoff reduction, property values, air quality, carbon dioxide reduction, and building energy use savings).

Fig. 23—Study area climate regions

Methods

Boundaries for the five Bay area climate regions were derived from California Energy Commission (CEC) climate regions (Fig. 23). As well, three tree zones (Fig. 24) that correspond to our reference city data collected in San Francisco (Maco et al. 2003), Berkeley (Maco et al. 2005), and Modesto (McPherson et al. 1999) were distinguished. Urban foresters were consulted to match available tree composition/structure and tree growth data with the appropriate Bay area region. Urban forest composition/structure and tree growth data were used from previous studies conducted in San Francisco (Maco et al. 2003; Nowak 2005), Berkeley (Maco et al. 2005), Oakland (Nowak 1991), Sacramento (McPherson 1998), and Modesto (McPherson et al. 1999).

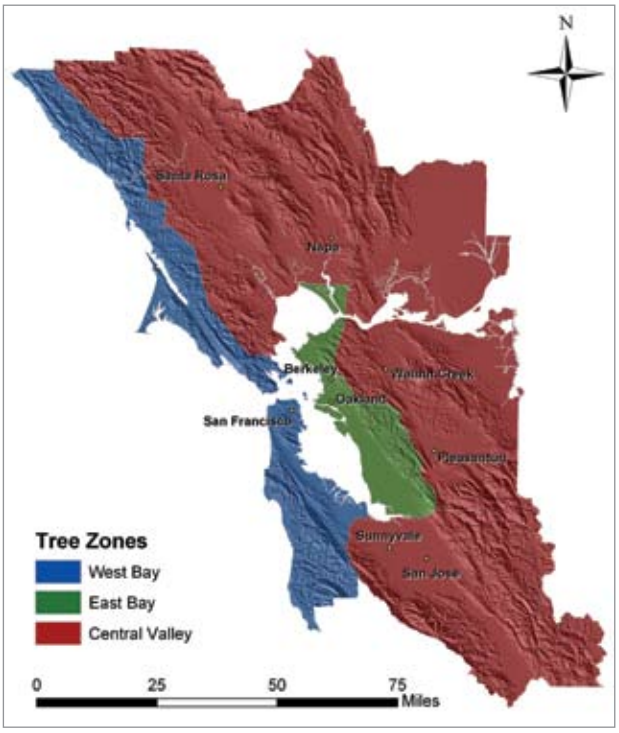

Fig. 24—The three tree zones: tree growth & species composition

Land Cover Analysis

ETM+ data from 2002 were used to determine tree cover, using methods described in Section 1. Tree cover/land use attribute tables were then joined to resource unit tables with a geographic

information system (GIS) in order to map the benefits of tree canopy cover by land use. Image data were divided into nine subsets, one for each county, from which all but urban areas defined by the 2000 census (Census 2002) were masked out. In the five cases where a county contained two climate regions, that county was split and spatial analysis was done separately for each portion of the county, resulting in a total of 14 separate areas for analysis.

Land use

The study area was mapped into six land use categories so that benefits of the urban tree cover could be applied by land use. Current (2005) land use data from the Association of Bay Area Governments (ABAG 2006) were used to map land use. These detailed data were reclassified to map the six general categories of interest for this study: 1 = commercial/ industrial, 2 = transportation, 3 = low-density residential (< 8 dwelling units per acre), 4 = high-density residential (≥ 8 dwelling units per acre), 5 = institutional and 6 = open space/ other. Benefits were linked to land use by adding a resource unit (RU) land use field (see next section) to the ABAG land use attribute table.

The previous studies from San Francisco, Berkeley, Oakland, Sacramento, and Modesto used different land use categories. In order to use the earlier data, the land use categories were cross-walked to the categories used in this study (Table 4). The institutional category includes schools, government sites, and parks. The open space category includes wild, vacant and agricultural land.

The ABAG land use vector data were converted to raster data to calculate canopy cover benefits based on land use. A GIS coordinate system was defined so the ESRI grid file could be imported. For this study the projected coordinate systems was NAD_1983_UTM_Zone_10N, and the geographic coordinate system was GCS_North_American_1983. After the land use data were converted to raster format, canopy cover by land use was calculated using the

Table 4—Land use category cross-walk. Land uses from previous studies were mapped into land uses on the left

Land use this study	Land use categories from previous studies			
	Oakland	**Sacramento**	**San Francisco**	**Berkeley**
Residential low	Residential	Residential low	Residential	Single-home residential
Residential high	Residential	Residential high	Residential	Multihome residential
Commercial / industrial	Commercial / industrial	Commercial / industrial	Commercial / industrial	Commercial / industrial
Institutional	Institutional	Institutional	Institutional / openspace	Institutional[1] / park
Open space	Wildland	Vacant / wild / agriculture	Vacant	Vacant / other[2]
Transportation	Transportation	Transportation	Street/row	Vacant / other[2]

[1] Government, schools, hospitals
[2] Agricultural, unmanaged areas of greenbelts

raster calculator tool in ESRIs ArcMap. This raster calculation produced a new raster map containing only the pixels within the selected land use including attributes for the relative abundances of the endmember. These attribute data were then exported as .dbf files and used in Excel to calculate land cover in square meters.

Resource Units

Value of benefits was determined from resource units (RUs), which are expressed in common engineering units, either per tree or per square foot of canopy cover (TCCA). RUs considered were electricity (kilowatt-hours [kWh] per tree or per square foot) and natural gas savings (1,000 British thermal units [kBtus] per tree or per square foot), net atmospheric carbon dioxide (CO_2) reductions (pounds per tree or per square foot), net air quality improvement (pounds per tree or per square foot), stormwater runoff reductions (precipitation interception - cubic feet per tree or per square foot) and property value increases (based on changes in amount of leaf surface area [LSA], given in dollars per square foot of LSA per tree or per square feet of LSA per square foot of TCCA). Prices were assigned through methods described below.

An important aspect of this study was to develop the necessary methodology to convert existing RUs, in the past expressed on a per tree basis, to per unit TCCA. Previous studies tabulated RUs per tree as a function of species and size; land use dependence was incorporated into the RUs and so not explicitly accounted for. Here existing RUs are functions of canopy cover and land use, accounting implicitly for species and size (age) composition for the tree population characteristic of each climate region and land use in the study area. The incorporation of species and size dependence in TCCA-based RUs facilitates the application to large areas through use of map-based (GIS) techniques. Mapping of climate regions and land use in this study allowed RUs, and hence benefits, to be customized for specific locations instead of assuming a statistical distribution of land uses and climate regions.

RU derivation involved four steps. First RUs per tree were calculated for each of the five climate regions based largely on three prior municipal forest resource analyses (MFRAs) done for San Francisco (Maco et al. 2003), Berkeley (Maco et al. 2005), and Modesto (McPherson et al. 1999). Data sources are detailed in Table 5, and include climate, building, pricing, environmental, tree species and air quality data. In the referenced MFRAs, RUs per tree and CPA or LSA per tree were calculated as a function of species and size class from a stratified random sample of approximately 20 species, for which 30–50 trees of each species were measured in each city to establish relations between tree age, size, leaf area and biomass. Trees were selected so as to represent as wide a range of sizes/ages possible; nine size classes were used. Tree spatial distribution defined by distance and directions from nearest building was also extracted from the data.

Table 5—San Francisco Bay area data and sources by climate region

Climate region	West Bay	East Bay	North Bay	South Bay	Central Valley
General data					
Major city	San Francisco	Oakland	Santa Rosa	San Jose	Walnut Creek
CEC zones[1]	3 (1 in north)	3	2	4	12
Counties	San Francisco, San Mateo, Marin (60%), Sonoma (20%)	Alameda (40%), Contra Costa (15%), Solano (10%)	Napa, Sonoma (80%), Marin (40%)	Santa Clara	Alameda (60%), Contra Costa (85%), Solano (90%)
Default data source	San Francisco[2]	Berkeley[3]	Modesto[4]	Modesto[4]	Modesto[4]
Canopy cover by spp.	San Francisco[5]	Oakland[6]	Sacramento[7]	Sacramento[7]	Sacramento[7]
Species composition, growth rates and age structure	San Francisco[2]	Berkeley[3]	Modesto[4]	Modesto[4]	Modesto[4]
BVOC base rates	San Francisco[2]	Berkeley[3]	Modesto[4]	Modesto[4]	Modesto[4]
Hourly pollutant concentrations					
Regional population[8]	1,546,049	1,529,901	844,449	1,734,721	1,293,579
Inflation factor[9]	1.59				
AQ model year	1999	2001	2002	2001	2002
Hourly AQ weather data	San Francisco[2]	Berkeley[3]	CIMIS 83[10]	CIMIS 69[4]	CIMIS 170[4]
PM_{10} highest arithmetic mean concentration (ug/m^3)[11]	26	20	20	29	21
PM_{10} location	Arkansas St, SF	San Pablo	Santa Rosa	120b N 4th St.	Concord
SO_2 highest arithmetic mean concentration (ppm)[12]	0.002	0.002	0.002	0.002	0.001
SO_2 location	Arkansas St, SF	Oakland	Vallejo	Oakland	Concord
O_3 2nd daily maximum 1-hr concentration (ppm)[13]	0.07	0.0776	0.1	0.105	0.102
O_3 location	Arkansas St, SF	Oakland	Santa Rosa	120b N 4th St.	Concord
Carbon dioxide					
Tree care CO_2 emissions (lb/in dbh) [14]	0.78	0.78	0.78	0.78	0.78
CO_2 price ($/ton)[15]	6.68	6.68	6.68	6.68	6.68
Electricity emissions factors[16]	PG&E/eGrid				
Fuel mix[17]	PG&E				
Building energy use					
Tree location distribution	San Francisco[2]	Berkeley[3]	Modesto[4]	Modesto[4]	Modesto[4]
Hourly energy TMY2 data[18]	San Francisco	San Francisco	Santa Rosa	Sunnyvale	Sacramento
Building construction[19]	Pacific SW region				
HVAC equipment saturations[20]	EIA zone 4				
Building vintage and type[8]	U.S. Census 2000				
CDD[21]	111	152	372	588	416
HDD[21]	2,919	2,863	2,898	2,306	3,555
Electric price ($/kWh)[22]	0.213	0.213	0.213	0.213	0.213
Natural gas price ($/therm)[23]	1.73	1.73	1.73	1.73	1.73
Foliation period	San Francisco[2]	Berkeley[3]	Modesto[4]	Modesto[4]	Modesto[4]
Shade coefficients	San Francisco[2]	Berkeley[3]	Modesto[4]	Modesto[4]	Modesto[4]

Climate region	West Bay	East Bay	North Bay	South Bay	Central Valley
Hydrology					
Hydrology station number	CIMIS 149	CIMIS 149	CIMIS 83	CIMIS 69	CIMIS 65
Hydrology model year	1999	2000	2002	2001	1992
Runoff value ($/gal)[24]	0.006	0.006	0.006	0.006	0.006
Property Value					
Median home price[25]	759,500	595,000	648,333	645,000	508,500
Large tree leaf area (ft^2)[26]	3,348	3,348	3,348	3,348	3,348
Tree land use distribution	San Francisco[2]	Berkeley[3]	Modesto[4]	Modesto[4]	Modesto[4]
Property value reduction[24]	0.834				
Mortality years 1-5[24]	2.32%				
Mortality >6 years[24]	1.48%				

[1]CEC 2006
[2]Maco et al. 2003
[3]Maco et al. 2005
[4]McPherson et al. 1999
[5]Nowak 2005
[6]Nowak 1991
[7]McPherson et al. 1998
[8]U.S. Census 2002
[9]Inflation factor corrects year 1989 values from Wang and Santini (1995) to year 2006
[10]CIMIS (California Irrigation Management Information System) station number
[11]Highest arithmetic (annual) mean concentration (ug/m^3) from EPA (U.S. EPA 2005)
[12]Highest arithmetic (annual) mean concentrations (ppm) (CDF 2002)
[13]Highest second daily maximum 1-hr ozone concentration (ppm) (CDF 2002)
[14]National average value (used in Berkeley, San Francisco, and Modesto studies
[15]Pearce et al. (2003)
[16]U.S. EPA 2003
[17]PG&E 2006
[18]NSRDB 2006
[19]Floor and window area, insulation, etc. (Ritschard et al. 1992)
[20]EIA (1993)
[21]Base 65, NCDC 1971–2000 Monthly Normals, WRCC (2006)
[22]PG&E 2005a
[23]PG&E 2005b
[24]Mean of values for San Francisco,[2] Berkeley,[3] and Modesto[4]
[25]DataQuick: www.dqnews.com/ZIPCAR.shtm
[26]*Fraxinus velutina* at 40 years, East Bay

The second step was to convert RUs per tree to RUs per unit TCCA for each species and size class represented:

$$RUs/TCCA_{i,j,k} = RUs/tree_{i,j,k} \div TCCA/tree_{i,j,k},$$

where *i* stands for climate region 1 to 5, *j* for size class 1 to 9, and *k* for species 1 to *n*, where *n* varies from 24 to 28 depending on climate region. In the third step, tree size dependence was removed by weighting RUs/TCCA by distribution of tree numbers by species and size class based on tree inventories supplied by cooperators in each of the cited MFRAs. In the final step, species dependence was removed and land use dependence added based on TCCA by species and land use data derived from the available earlier studies. San Francisco was used for the West Bay (Nowak 2005), Oakland for the East Bay (Nowak 1991), and Sacramento for the North Bay, South Bay and Central Valley (McPherson 1998). Reported leaf area for San Francisco was converted to CPA (canopy cover) using leaf area indexes (LAI) derived from sample inventory data in Maco et al. (2003). Crown widths (CW) reported for Sacramento were converted to CPA with the expression $CPA = \pi(CW/2)^2$. Data were manipulated to reconcile differences in land use designations among studies (Table 4).

RU conversions removed explicit tree size and species dependence and added land use dependence. Calculations were done for each unique county/climate region (14 total). Results were applied to land use maps derived as described earlier to determine benefit values for any given region.

Air quality benefit is computed as the net value of pollution removal by dry deposition, pollutant emissions avoided due to energy savings, and emission of biogenic volatile organic hydrocarbons (BVOCs) from trees. Dry deposition includes ozone, nitrogen dioxide (NO_2), particulate matter smaller than 10 microns in diameter (PM_{10}), and sulfur dioxide (SO_2). Avoided pollution includes NO_2, PM_{10}, SO_2 and volatile organic compounds (VOCs) from sources other than trees.

Tree numbers

Canopy cover was converted to estimates of tree numbers based on the average tree canopy diameter (D) of 5 m (16.4 ft) found for Sacramento (McPherson 1998). Canopy diameter was converted to horizontal crown projection area (CPA) by assuming a circular crown, where $CPA = \pi r^2$ and $r = D/2$, so that average CPA = 19.6 m^2 (211 ft^2).

Benefits

Calculation of benefits using GIS for each climate region (*i* = 1 to 5) and land use (*m* = 1 to 7) was a straightforward process, being the product of RUs per unit TCCA, tree size class distribution (TDist) and TCCP summed over size class (*j* = 1 to 9), and species (*k* = 1 to *n*), where *n* ranges from 24 to 28 depending on climate region:

$$Benefit_{i,m} = \sum_{k=1}^{n}\left[\sum_{j=1}^{9}\left[RUs/TCCA_{i,j,k} \times TDist_{i,j,k}\right] \times TCCP_{k,m}\right]$$

Results and Discussion

Land use

Residential land uses account for 46 percent of all urban land in the Bay Area, followed by transportation (21 percent), open space/other (15 percent), commercial/industrial (14 percent) and institutional (5 percent) (Table 6). Santa Clara County land use is mapped as an example (Fig. 25). Commercial and industrial land uses tend to be associated with urban centers, while residential land uses are more common on the urban fringe.

Table 6—Urban land area by county and land use (km²)

County	Residential low	Residential high	Commercial / industrial	Institutional	Transpor-tation	Open space	Total
Alameda	157	78	92	29	127	72	556
Contra Costa	205	63	65	27	91	101	553
Marin	67	10	16	1	28	29	152
Napa	23	7	3	2	10	16	61
San Francisco	2	39	11	5	32	25	114
San Mateo	95	35	30	14	64	36	276
Santa Clara	272	52	108	42	151	67	692
Solano	70	9	25	8	52	39	204
Sonoma	78	24	27	8	24	20	181
Bay Area	971	318	378	137	579	406	2,789

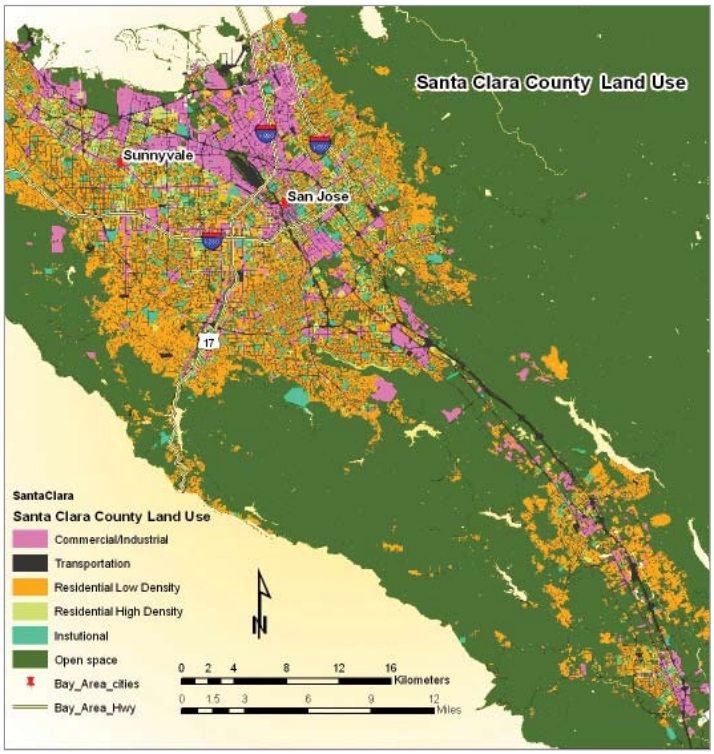

Fig. 25—Santa Clara County land use

Land Cover Analysis

Urban land use for Bay area counties ranged from 3 to 95 percent , and averaged 16 percent for the entire nine-county region (Table 7). Average canopy cover was 29 percent, ranging from 16 percent for San Francisco County to 47 percent for Marin County (Table 7). Canopy cover in San Francisco based on an Urban Forest Effects (UFORE) model study (Nowak et al. 2007) averaged 19.8%. The fact that the current analysis used remotely sensed data to determine combined tree and shrub canopy cover, while the UFORE analysis used measurements from ground sample plots, may partially explain the differences.

Land cover by land use for the Bay Area is given in Table 8. Canopy cover percentages are based on standard definitions (see introductory section "Definitions"). Total urban land area percent represents the fraction of urban land covered by each of the six listed land uses. Average canopy cover for the study area ranged from 40 percent for low density residential areas to 15 percent for commercial/industrial settings, and 29 percent overall (Table 8). A complete breakdown of cover data by land use for each county is given in Appendix 1.

Table 7—Land cover and population data by county for the Bay Area

County	Total area[1] (km^2)	Urban area[2] (km^2)	Urban area (percent)	Population	Tree canopy cover (percent)
Alameda	1,910	556	29.1	1,448,905	23.4
Contra Costa	1,865	553	29.6	1,017,787	31.3
Marin	1,346	152	11.3	246,960	46.8
Napa	1,952	61	3.1	132,764	34.1
San Francisco	121	114	94.6	793,426	16.1
San Mateo	1,163	276	23.7	699,610	31.7
Santa Clara	3,343	692	20.7	1,699,052	28.9
Solano	2,148	204	9.5	411,593	22.7
Sonoma	4,082	181	4.4	466,477	33.7
Bay Area	17,929	2,789	15.6	6,916,574	29

[1]CDL 2004
[2]U.S. Census 2002

Table 8—Urban tree cover and urban area by land use for the Bay area

Land cover	Residential low	Residential high	Commercial / industrial	Institutional	Transportation	Open space	Total
Tree canopy cover (km^2)	392	86	55	33	139	102	808
Tree canopy cover (%)	40.3	27.1	14.7	24.3	24	25.3	29
Total urban land (km^2)	971	318	378	137	579	406	2,788
Total urban land (%)	34.8	11.4	13.5	4.9	20.8	14.6	100
Tree numbers (millions)	19.9	4.4	2.8	1.7	7.1	5.2	41.2

Canopy cover for the urbanized portion of Marin County is mapped as an example (Fig. 26), where it can be seen that urban development is clustered on the eastern, bay side of the county. This figure also illustrates why some counties were divided into two climate regions.

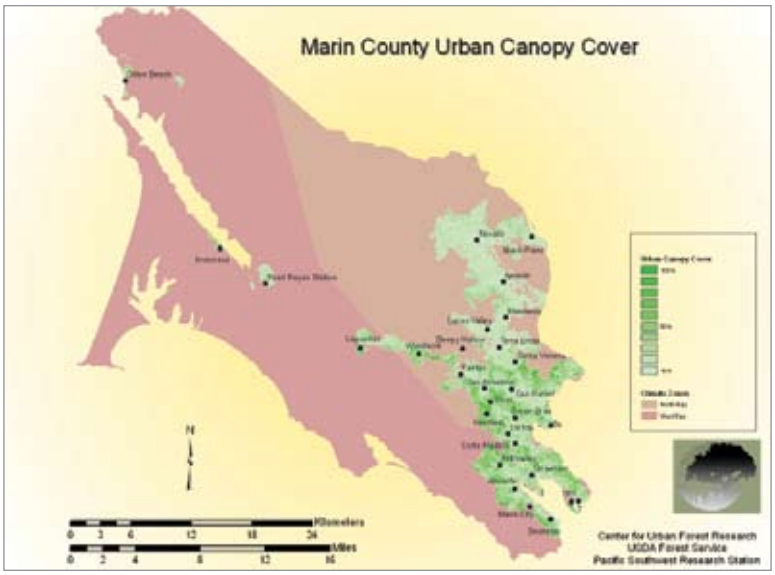

Fig. 26—Canopy cover for urbanized Marin County

Resource Units

Resource units (RUs) for the five climate regions are given in Appendix 2. Values are given in both engineering units (e.g. mass, volume, energy) and dollars per unit of canopy cover area (m^2).

Tree Numbers

There are about 41 million urban trees in the Bay area (Table 9) based on an average CPA of 19.6 m^2 (211 ft^2) (crown diameter of 5.0 m [16.4 ft]). Tree numbers calculated in this way are sensitive to relatively small changes in crown diameter used. For example, Nowak (2005) found 669,000 trees in San Francisco County in a study based on counting trees is sample plots, compared to 940,000 calculated here (Appendix 1). Increasing the estimated crown diameter in our calculations by 3 ft (0.9 m) to 19.4 ft (5.9 m) reduces the number of trees estimated here to about 670,000.

Benefits

Annual benefits for the region were estimated at $4.9 billion (Table 10) based on canopy area for each county and land use. They are broken down by

Table 9—Estimated tree numbers by land use for the study area based on 16.4 ft crown diameter

County	Residential low	Residential high	Commercial / industrial	Institu-tional	Transpor-tation	Open space	Total
Alameda	2,724,021	1,022,626	499,470	336,715	1,214,680	816,215	6,613,727
Contra Costa	4,485,056	1,001,028	461,773	351,419	1,266,071	1,242,589	8,807,936
Marin	1,934,046	230,448	221,268	14,942	597,751	622,206	3,620,661
Napa	511,072	114,543	28,154	39,948	155,432	211,388	1,060,536
San Francisco	29,467	262,073	28,910	50,199	154,551	414,802	940,002
San Mateo	2,265,537	406,219	200,286	192,090	858,585	536,170	4,458,887
Santa Clara	5,237,207	755,067	978,935	510,025	1,948,805	767,078	10,197,118
Solano	1,143,067	128,024	150,710	77,120	496,796	363,157	2,358,874
Sonoma	1,630,191	462,904	251,003	115,790	394,652	260,454	3,114,994
Bay Area	19,959,664	4,382,932	2,820,508	1,688,248	7,087,323	5,234,060	41,172,735

benefit type and tabulated for each county and land use in Appendix 3. Totals in millions of dollars are summarized in Table 10. The largest fraction of benefits was associated with low-density residential land use (70 percent), the least with transportation (< 1 percent), with 11, 10, 6 and 3 percent for high-density residential, open space, commercial/industrial and institutional, respectively. Larger counties with sizeable residential populations had the greatest total benefits (e.g. Santa Clara, Contra Costa, Alameda).

Comparison of benefits with previous work done by the Center for Urban Forest Research is facilitated by conversion of results to a per-tree basis (Table 11). We expected differences in results because the simulations for this study used more recent median home sales prices, and different benefit prices, tree mortality rates, and average tree sizes. A value of $89 per tree was found for Berkeley (Maco et al. 2005), compared to $104 per tree here, an increase of 17 percent. A similar analysis for San Francisco yielded $77 per tree (Maco et al. 2003), compared to $110/tree found here, an increase of 43 percent. Differences between studies are similar to the increases in property values that occurred between studies, which were 13 percent for Berkeley and 39 percent

Table 10—Total net benefits by county and land use (millions of dollars)

County	Residential low	Residential high	Commercial / industrial	Institutional	Transportation	Open space	Total
Alameda	422	118	46	27	3	73	690
Contra Costa	666	109	41	25	3	102	946
Marin	363	32	24	1	2	66	487
Napa	93	15	3	4	0	21	136
San Francisco	6	39	3	5	1	49	103
San Mateo	446	60	23	21	5	64	617
Santa Clara	1,136	121	123	56	5	94	1,535
Solano	171	14	13	6	1	29	233
Sonoma	297	61	26	10	1	26	422
Bay Area	3,599	569	303	155	22	524	5,171

Table 11—Total net benefits (dollars/tree) by county and land use

County	Residential low	Residential high	Commercial / industrial	Institutional	Transportation	Open space	Total
Alameda	156	116	95	80	3	90	105
Contra Costa	151	110	91	72	2	82	109
Marin	189	139	109	89	4	106	136
Napa	185	134	107	89	3	99	130
San Francisco	197	148	114	107	5	119	110
San Mateo	197	148	114	107	5	119	139
Santa Clara	181	132	107	89	3	99	125
Solano	152	109	90	72	2	80	100
Sonoma	185	134	107	89	3	99	137
Bay Area	172	126	102	86	3	97	120

for San Francisco. Hence, benefit values reported here are reasonable when compared with previously reported findings from similar analyses for the same region. A summary of tree numbers, current canopy cover, and benefits by county is given in Table 12.

Current canopy cover, urban area, population, tree density, numbers of trees based on an average crown diameter of 16.4 ft (5.0 m), and resulting benefits are summarized in Table 12, sorted by total benefits in millions of dollars. Total benefits are approximately proportional to urban area, number of trees, and population (the latter is approximately proportional to urban area). However, a smaller county such as Marin is elevated in the standings due to its relatively dense tree cover.

Benefits are broken down by type (e.g., hydrology, air quality, electricity) for each county in Table 13. Property value enhancement accounts for 91 percent of total benefits, followed by energy (electricity and natural gas) at 6 percent, stormwater runoff (hydrology) at 2 percent, and fractional percentages for air quality and carbon dioxide. Air quality benefits from deposition and

Table 12—Summary of current tree canopy cover and benefits by county

County	Canopy cover (%)	Urban area (km^2)	Population	Tree density (trees/ha)	Trees (M)	Trees/ capita	Benefits (millions of $)	$/tree	$/capita
Alameda	23.4	556	1,448,905	119	6.6	4.6	690	104	476
Contra Costa	31.3	553	1,017,787	159	8.8	8.7	946	107	930
Marin	46.8	152	246,960	238	3.6	14.7	487	135	1,973
Napa	34.1	61	132,764	174	1.1	8	136	128	1,026
San Francisco	16.1	114	793,426	82	0.9	1.2	103	110	130
San Mateo	31.7	276	699,610	162	4.5	6.4	617	138	883
Santa Clara	28.9	692	1,699,052	147	10.2	6	1,535	151	903
Solano	22.7	204	411,593	116	2.4	5.7	233	99	567
Sonoma	33.7	181	466,477	172	3.1	6.7	422	135	905
Total	29	2,789	6,916,574	148	41.2	6	5,171	126	748

Table 13—Value of current benefits (thousands of dollars) by benefit type and county

County	Hydrology	Property value	Air quality	CO_2	Natural gas	Electricity	Total
Alameda	14,479	638,468	−7	723	4,583	32,139	690,384
Contra Costa	17,238	833,262	1,262	828	6,340	87,376	946,307
Marin	10,633	447,483	752	336	4,515	23,546	487,267
Napa	2,185	123,084	236	91	1,700	8,961	136,256
San Francisco	4,444	98,273	165	66	83	446	103,476
San Mateo	20,575	588,349	798	438	933	6,332	617,426
Santa Clara	21,821	1,411,399	4,630	950	1,514	94,611	1,534,925
Solano	4,569	205,552	297	219	1,670	20,961	233,268
Sonoma	6,475	377,377	712	288	6,042	31,053	421,947
Bay Area	102,419	4,723,247	8,844	3,940	27,380	305,426	5,171,256

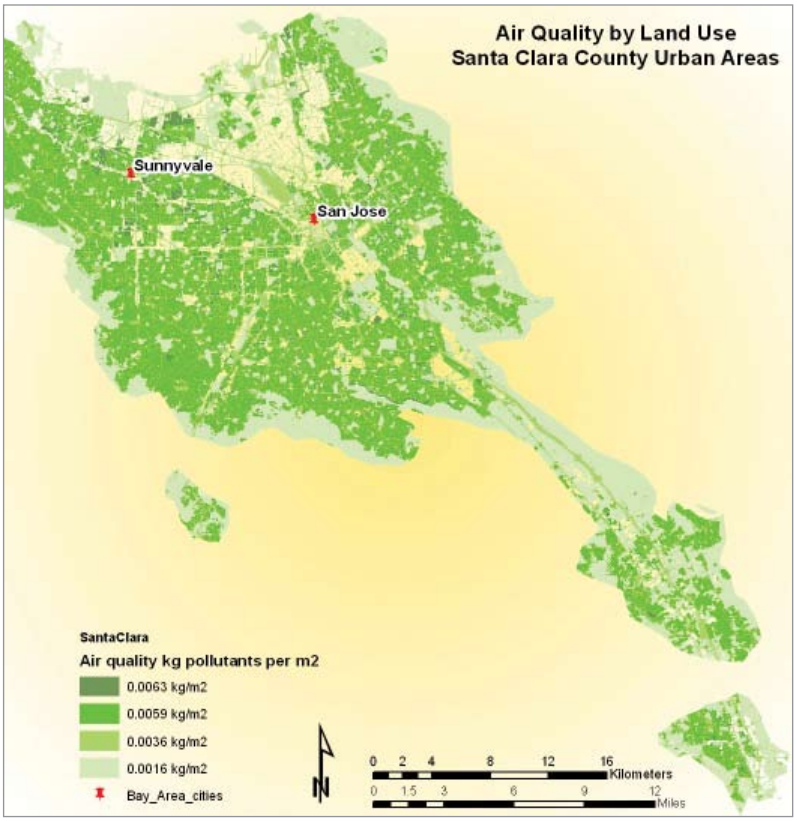

Fig. 27—Variation in annual air quality benefits for urbanized Santa Clara County

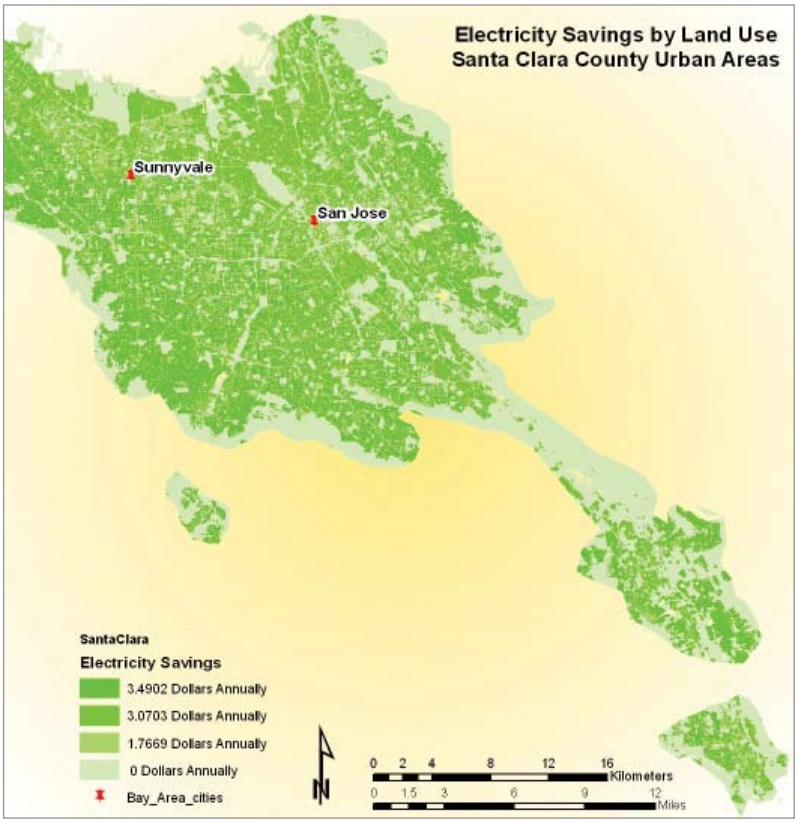

Fig. 28—Variation in annual electricity savings benefits for urbanized Santa Clara County

avoided pollution are offset to differing degrees by BVOC emissions. In Alameda County the value of BVOC emissions was greater than the savings resulting from deposition and avoided pollution, resulting in a negative value for San Francisco and Berkeley. Air quality effects were also found to be a net cost in an earlier analysis by Maco et al. (2005).

Benefits can be mapped in different ways for the study area. For example, individual benefits are mapped for urbanized Santa Clara County for air quality (Fig. 27), electrical energy savings (Fig. 28) and total benefits (Fig. 29).

Selected results were compared with an Urban Forest Effects (UFORE) model study for San Francisco (Nowak et al. 2007). Gross carbon sequestration of approximately 18,700 tons CO_2 (5,100 tons carbon) was reported in the UFORE analysis, which compares favorably with the 20,920 tons CO_2 reported here (Appendix 3). Total deposition of ozone, NO_2, PM_{10}, and SO_2 in the UFORE study was approximately 248 tons compared with 168 tons here. The difference may be due in part to differences in input data and methodology between studies. For example, UFORE analysis used year 2000 pollution and weather data, while the current analysis used data from 1999. In addition, canopy cover in the UFORE analysis was somewhat higher than found here (19.8 vs. 16.1%).

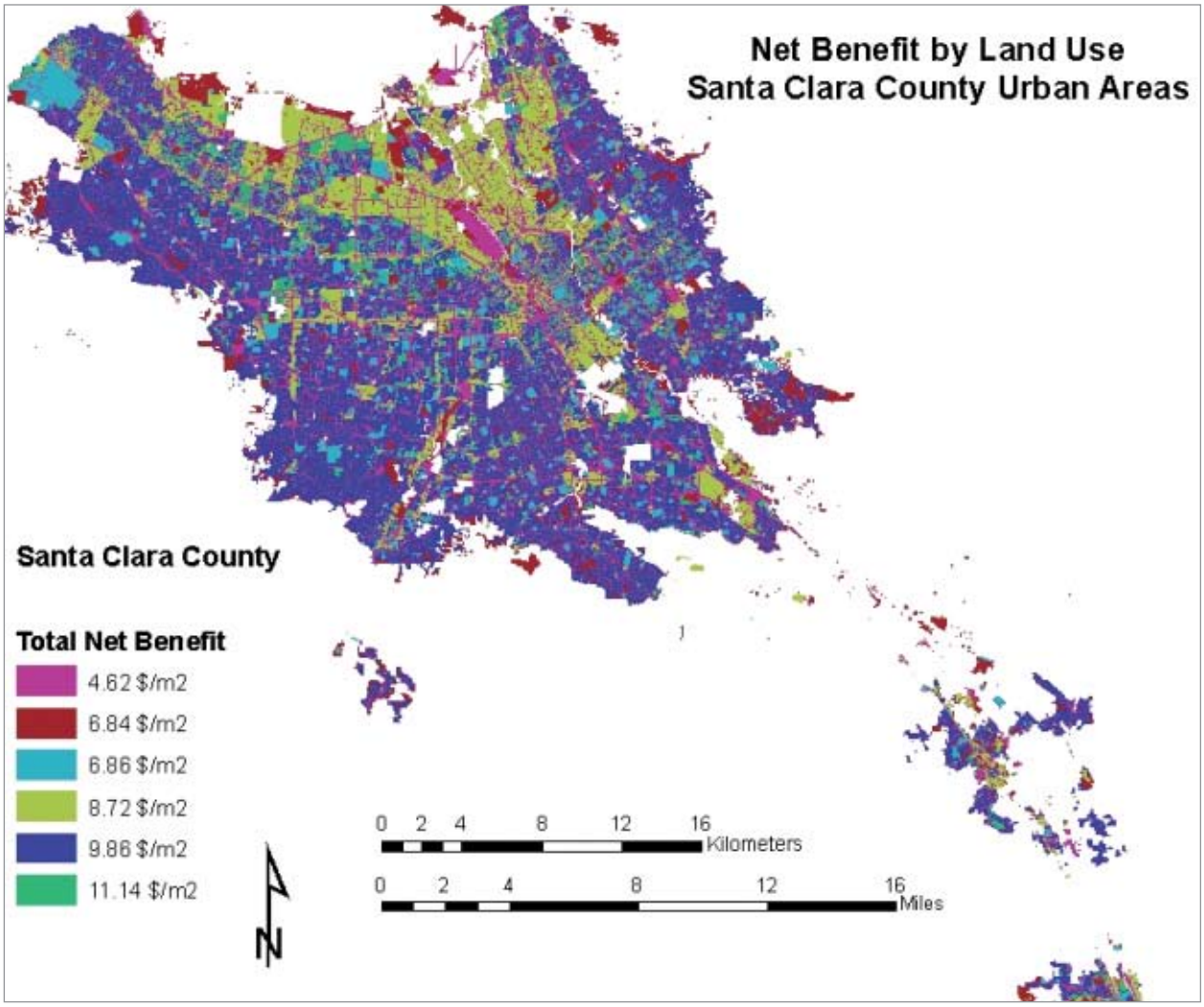

Fig. 29—Variation in annual net benefits for urbanized Santa Clara County

III. Value of Future Benefits

Methods

Value of future benefits depends primarily upon changes in the future canopy cover, which in the current analysis depends primarily on future tree planting and survival rates (e.g., quality of nursery stock, planting conditions, level of tree care). Canopy cover also differs with land use, so land use changes driven by urban growth and development will also influence future canopy cover. For this analysis, canopy cover increases of 1.5, 3, 6, and 9 percent were used to illustrate effects of various levels of canopy cover change. Increases in tree canopy cover were applied in the same proportions as existing canopy cover.

Projections of future changes in land use were not available for the Bay area. Consequently, it was assumed for this analysis that land use changes occurred within current urbanized boundaries, reflected as conversion of pervious cover type. Tree canopy cover targets used were well within similar targets that have been set in other locations (Table 14; McPherson et al. 2007)

Table 14—Existing, projected and increase in tree canopy cover targets (percent) for selected cities

City	Existing	Target	Increase
New York City, NY	23	30	7
Baltimore, MD	20	46	26
Vancouver, WA	20	28	8
Roanoke, VA	32	40	8
Portland, OR	26	46	20
Los Angeles, CA	21	28	7

Results and Discussion

Tree number increases ranged from 2 to 13 million, or 5 to 31 percent (Table 15). Notice that "Canopy cover increase" in this table refers to actual canopy cover and not it's relative change, i.e. a 3 percent canopy cover increase from 29 to 32 percent represents a change in canopy cover (and tree numbers) of approximately 10 percent. Total numbers of trees including these increases range from 41 million to 54 million based on a 16.4 ft tree crown diameter. Benefits increase approximately in proportion to the change in tree numbers. Increased canopy cover resulted in added benefits ranging from $240 million (4.6 percent) to $1.4 billion (27.5 percent), and total benefits from all trees ranged from $5.2 to $6.6 billion.

Table 15—Projected increase in tree numbers and benefits for selected canopy cover changes

Canopy cover increase (%)	Canopy cover (%)	Trees	Tree increase	Benefit (millions of $)	Benefit increase (millions of $)	Benefit increase (%)
0	29	41,172,735	0	5,171	0	0.00
1.5	30.5	43,304,206	2,131,470	5,409	237	4.60
3	32	45,435,676	4,262,940	5,646	475	9.20
6	35	49,698,616	8,525,881	6,121	949	18.40
9	38	53,961,556	12,788,821	6,595	1,424	27.50

Benefits are largest for single family residential land use (~70 percent), with smaller contributions from high density residential (11 percent), open space (10 percent), commercial/industrial (6 percent), institutional (3 percent) and transportation (<1 percent) (Fig. 30, Table 16).

Based on experience in Sacramento (Kerth 2007), a planting goal of approximately 4 million trees over a 20-year period was selected for more detailed analysis, which corresponds to the 3-percent canopy cover increase. The projected increase of 4.3 million trees results in added benefits of $475 million, or $69 per capita (Table 17). Increases in tree cover are distributed in proportion to existing tree numbers, so that counties like Santa Clara and Contra Costa experience the largest increases. Per capita benefits tend to be higher where urban areas are less densely populated, e.g. Marin and Napa counties.

Projected change in benefits by benefit type and county (Table 18) reflects a pattern similar to that of current benefits (Table 13).

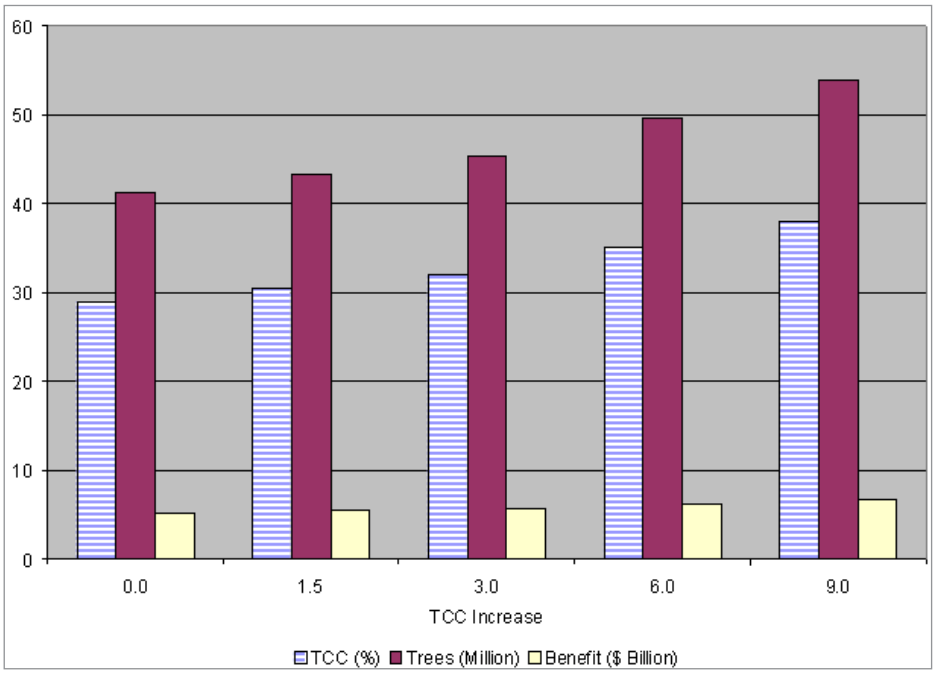

Fig. 30—Change in tree canopy cover, number of trees and total benefits for selected future growth scenarios

Table 16—Projected change in total benefits (millions of dollars) by land use for selected increases in canopy cover

Canopy cover (%)	Residential low	Residential high	Commercial / industrial	Institutional	Transportation	Open space	Total
29	3,599	569	303	155	22	524	5,171
30.5	3,733	601	333	165	23	554	5,409
32	3,866	632	363	175	25	585	5,646
35	4,133	696	424	194	27	646	6,121
38	4,400	760	485	213	30	707	6,595

Table 17—Projected tree numbers and benefits by county for a 3-percent increase in tree canopy cover

County	Existing trees (thousands)	New trees (thousands)	Existing benefits (millions $)	Added benefits (millions $)	New trees/ capita	Added benefits ($/capita)
Alameda	6,614	849	690	78	0.6	**54**
Contra Costa	8,808	845	946	82	0.8	81
Marin	3,621	232	487	29	0.9	118
Napa	1,061	93	136	11	0.7	84
San Francisco	940	175	103	17	0.2	22
San Mateo	4,459	422	617	51	0.6	73
Santa Clara	10,197	1,058	1,535	144	0.6	85
Solano	2,359	311	233	27	0.8	65
Sonoma	3,115	277	422	35	0.6	75
Bay Area	41,173	4,263	5,171	475	0.6	69

Table 18—Projected change in benefits (thousands of dollars) by benefit type for a 3-percent increase in canopy cover

County	Hydrology	Property value	Net air quality	Carbon dioxide	Natural gas	Electricity	Total
Alameda	1,892	71,667	−21	92	802	3,747	78,179
Contra Costa	1,662	72,744	90	77	705	6,878	82,155
Marin	660	26,645	47	21	286	1,420	29,079
Napa	190	10,069	20	8	130	671	11,088
San Francisco	833	16,031	31	13	34	119	17,060
San Mateo	1,987	48,664	75	39	115	527	51,407
Santa Clara	2,239	132,019	452	95	223	8,780	143,808
Solano	600	23,577	30	28	246	2,234	26,714
Sonoma	567	31,459	60	25	517	2,542	35,170
Bay Area	10,631	432,874	783	397	3,057	26,918	474,661

Summary and Conclusions

The urban environment in the San Francisco Bay Area has rapidly expanded into predominately rangeland and agricultural areas. A population increase of 30 percent has driven a 73-percent increase in urban area. The increase in urban area is associated with a 10-percent increase in canopy cover, but this increase has not kept pace with the 17-percent increase in impervious surfaces. With the exception of San Jose, the pattern of urban growth or increase in urban extent has been in the urban fringe areas outside the immediate vicinity of the San Francisco Bay.

Urban land uses comprised 16 percent of the region. Canopy cover for the study area ranged from 40 percent for low-density residential areas to 15 percent for commercial/industrial settings. The overall average was 29 percent, which represents approximately 41 million trees. Residential land uses account

for 46 percent of all urban land in the Bay Area, followed by transportation (21 percent), open space/other (15 percent), commercial/industrial (14 percent) and institutional (5 percent).

Total annual benefits from existing trees were about $5 billion ($125/tree, $750/capita). Property value enhancement accounts for 91 percent of total benefits, followed by energy (electricity and natural gas) at 6 percent, stormwater runoff (hydrology) at 2 percent, and fractional percentages for air quality and carbon dioxide. Most benefits are associated with low-density residential land use (70 percent), the least with transportation (<1 percent), with 11, 10, 6 and 3 percent for high-density residential, open space, commercial/industrial and institutional land uses, respectively.

Future projections of the effects of 1.5 to 9 percent increases in tree canopy cover were used to assess possible changes in benefits. Benefits corresponding to these tree canopy cover changes ranged from 5 to 28 percent, or $240 million to $1.4 billion. More detailed analysis of a 4.3 million tree (3 percent) increase in canopy cover showed added benefits of $475 million, or $69 per capita. Counties with the most trees currently, such as Santa Clara and Contra Costa, experienced the largest increases. Per capita benefits tended to be higher where urban areas are less densely populated, e.g. Marin and Napa counties.

Many factors are at work to determine the relative magnitude and ranking of the benefits of tree cover in each county. Important factors include urban area, number of trees, and level of tree cover, and how these are projected to change over time. Other factors relevant to this study include relative air quality, climate, tree species and real estate valuations (Table 5). There a number of other parameters, such as air, water and energy prices, fuel mix, emission factors and building construction (see Table 5) that, under different circumstances such as a comparison between widely separated geographic areas, could give rise to additional differences in the results.

The present analysis does not explicitly account for possible changes in urban boundaries over time that often accompany urban growth. Since urban growth has predominantly been into agricultural and rangeland areas, it would likely result in an increase in canopy cover. Consequently, tree cover increases applied here to existing urban areas would apply to urbanizing areas if the tree cover increases were interpreted as net changes relative to the pre-existing tree canopy cover.

Recommendations

Existing tree canopy cover is a valuable asset that needs to be preserved and protected. Information on the projected benefits of a substantial tree planting program in the San Francisco Bay area will prove valuable for the region and its residents.

To manage and disseminate this information we suggest the following:

- A regional entity, such as the Association of Bay Area Governments, establish a central clearinghouse for current data related to the San Francisco Bay Area State of the Urban Forest program. Data from this and proposed studies could be accessed through the clearinghouse.
- The regional entity develop a handout that summarizes key points from this study, particularly the future benefits to be gained from investment in tree planting and stewardship.
- All aspects of this research be documented and this report be made readily accessible through the clearinghouse.

Information on the benefits of a large-scale tree planting program can be helpful in developing partnerships with investors. For example, corporations may invest in the program because they can report carbon credits from trees that help offset their emissions. Similarly, if the Bay Area Air Quality Management District were to include trees as an air quality improvement measure in their State Implementation Plan, more funds for tree planting and management would become available. To capitalize on these opportunities, a Bay area program would need a credible process for tracking tree planting and monitoring the survival, growth, and functionality of its trees. To attract serious investment, the program will have to demonstrate that the benefits from these trees will be permanent and quantifiable. To do this will entail a commitment to accountability through annual monitoring and reporting.

The Center for Urban Forest Research could work with a Bay Area program to develop a more detailed analysis with higher resolution GIS data that identifies potential planting spaces at the parcel scale, such as was recently completed by the Center for the city of Los Angeles (McPherson et al. 2007). Such a study would develop a high-resolution (2 m compared to the 30 m used in the current study) description of current canopy cover, and pervious and impervious surface. This information could then be used to identify the approximate number of tree planting sites by tree type (i.e., deciduous vs. evergreen, and large, medium, small sizes) and show their distribution across the region. Scenarios thus developed would be suitable for estimating benefits associated with future tree planting.

The Center is currently investigating the development of a GIS Decision Support System (GDSS) to provide a user-friendly interface for planning and implementation of neighborhood tree planting projects by tree planting coordinators such as Friends of the Urban Forest, Our City Forest, Urban Releaf and CityTrees. Our GDSS would allow users without extensive GIS experience to examine different parcels, select and locate trees to provide the greatest benefits, budget for planting and maintenance costs, project the future stream of benefits, assess the ecological stability of the planting at a population level, and track future tree survival and growth. The GDSS would help the Bay

area maximize its return on investment in tree planting through application of state-of-the-art science and technology. Development of such functionality is necessary for individual cities and municipalities to be able to fully utilize the data at the local level.

We estimate that up to 20% of potential planting spaces in the Bay area are located in paved parking lot areas. Planting trees in parking lots poses technical and financial challenges. However, if done judiciously, there are opportunities for parking lot tree plantings to substantially improve air quality, reduce stormwater runoff, cool urban heat islands, and improve community attractiveness. We recommend that the regional entity establish new partnerships aimed at developing the technical specifications, financial means, and community support for a major parking lot greening effort.

The Center proposes to collaborate with other scientists in northern California to study the effects of trees on the social, economic, and environmental health of the Bay area and its nearly seven million residents. In particular, we need to better understand:

- Barriers to tree planting and incentives for different markets
- Effects of trees on the urban heat island and air quality
- Effects of drought stress on tree survival and ability to remove air pollutants
- Primary causes of tree mortality
- Best management practices to promote tree survival
- Citywide policy scenarios to promote urban tree canopy, neighborhood desirability, and economic development
- How to link tree canopy cover goals to other city goals: increasing community health, neighborhood quality of life, environmental literacy, and sustainability.

As the one of the largest metropolitan areas in the United States, the cities and counties of the Bay area manage an extensive municipal forest. Its management should set the standard for the state and the country. We recommend that administrative units around the Bay area and the Center for Urban Forest Research cooperate to conduct tree inventories and assessments that provide the following information on the existing urban forest:

- Structure (species composition, diversity, age distribution, condition)
- Function (magnitude of environmental and aesthetic benefits)
- Value (dollar value of benefits realized)
- Management needs (sustainability, maintenance, costs)
- Management recommendations aimed at increasing resource sustainability

The San Francisco Bay area is a vibrant region that will continue to grow. As it grows it should also continue to invest in its tree canopy. This is no easy task, given financial constraints and trends toward higher density development that may put space for trees at a premium. The challenge ahead is to better integrate the green infrastructure with the gray infrastructure by increasing tree planting, providing adequate space for trees, adopting realistic tree canopy cover targets, and developing strategies, plans, programs, and municipal assessments to maximize net benefits over the long term, thereby perpetuating a resource that is both functional and sustainable. The Center looks forward to working with Bay area municipalities and their many professionals to meet that challenge in the years ahead.

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Appendix 1. Land use, population, and canopy cover

Tables 19 and 20 present information for the studied nine counties on land use, population, and canopy cover.

Table 19—Land cover and population summary by county

	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	Total
Population[1]	1,448,905	1,017,787	246,960	132,764	793,426	699,610	1,699,052	411,593	466,477	6,916,574
Total area (km^2)	1,910	1,865	1,346	1,952	121	1,163	3,343	2,148	4,082	17,929
Urban area (km^2)[1]	556	553	152	61	114	276	692	204	181	2,789
Urban area (%)	29.10	29.60	11.30	3.10	94.60	23.70	20.70	9.50	4.40	15.60
Canopy cover (%)	23.40	31.30	46.80	34.10	16.10	31.70	28.90	22.70	33.70	29.00

[1]U.S. Census 2002

Table 20—Land use and canopy cover for the nine studied counties

County	Land cover	Residential low	Residential high	Commercial / industrial	Institutional	Transportation	Open space	Total
Alameda	Canopy cover (m²)	53,458,640	20,068,943	9,802,046	6,608,003	23,837,970	16,018,147	129,793,748
	Canopy cover (%)	33.90	25.70	10.60	23.10	18.80	22.10	23.40
	Total urban land (m²)	157,489,000	78,114,070	92,211,500	28,571,710	126,843,935	72,373,100	555,603,315
	Total urban land (%)	28.30	14.10	16.60	5.10	22.80	13.00	100.00
	Tree numbers	2,724,021	1,022,626	499,470	336,715	1,214,680	816,215	6,613,727
Contra Costa	Canopy cover (m²)	88,018,789	19,645,070	9,062,249	6,896,571	24,846,516	24,385,694	172,854,890
	Canopy cover (%)	42.90	31.10	14.00	25.40	27.30	24.10	31.30
	Total urban land (m²)	205,345,000	63,258,000	64,523,500	27,124,330	91,110,000	101,309,500	552,670,330
	Total urban land (%)	37.20	11.40	11.70	4.90	16.50	18.30	100.00
	Tree numbers	4,485,056	1,001,028	461,773	351,419	1,266,071	1,242,589	8,807,936
Marin	Canopy cover (m²)	37,955,468	4,522,519	4,342,353	293,232	11,730,807	12,210,741	71,055,120
	Canopy cover (%)	56.50	43.60	26.50	30.30	42.50	41.60	46.80
	Total urban land (m²)	67,208,000	10,378,930	16,402,560	969,014	27,633,550	29,368,510	151,960,564
	Total urban land (%)	44.20	6.80	10.80	0.60	18.20	19.30	100.00
	Tree numbers	1,934,046	230,448	221,268	14,942	597,751	622,206	3,620,661
Napa	Canopy cover (m²)	10,029,744	2,247,886	552,514	783,973	3,050,340	4,148,461	20,812,918
	Canopy cover (%)	43.30	34.50	16.20	35.30	31.40	26.00	34.10
	Total urban land (m²)	23,178,400	6,519,120	3,403,330	2,218,250	9,714,510	15,951,000	60,984,610
	Total urban land (%)	38.00	10.70	5.60	3.60	15.90	26.20	100.00
	Tree numbers	511,072	114,543	28,154	39,948	155,432	211,388	1,060,536
San Francisco	Canopy cover (m²)	578,287	5,143,159	567,363	985,146	3,033,047	8,140,451	18,447,452
	Canopy cover (%)	31.80	13.10	5.20	18.00	9.60	32.40	16.10
	Total urban land (m²)	1,817,820	39,273,100	10,953,200	5,463,190	31,711,900	25,147,300	114,366,510
	Total urban land (%)	1.60	34.30	9.60	4.80	27.70	22.00	100.00
	Tree numbers	29,467	262,073	28,910	50,199	154,551	414,802	940,002

Table 20, cont.

County	Land cover	Residential low	Residential high	Commercial / industrial	Institutional	Transportation	Open space	Total
San Mateo	Canopy cover (m²)	44,460,941	7,972,006	3,930,591	3,769,750	16,849,639	10,522,293	87,505,220
	Canopy cover (%)	46.60	22.60	13.00	26.40	26.20	28.90	31.70
	Total urban land (m²)	95,387,400	35,306,100	30,330,200	14,283,400	64,368,400	36,358,700	276,034,200
	Total urban land (%)	34.60	12.80	11.00	5.20	23.30	13.20	100.00
	Tree numbers	2,265,537	406,219	200,286	192,090	858,585	536,170	4,458,887
Santa Clara	Canopy cover (m²)	102,779,678	14,818,120	19,211,499	10,009,194	38,245,112	15,053,835	200,117,440
	Canopy cover (%)	37.70	28.70	17.80	23.90	25.30	22.50	28.90
	Total urban land (m²)	272,421,000	51,620,900	107,836,000	41,799,200	151,328,087	66,865,200	691,870,387
	Total urban land (%)	39.40	7.50	15.60	6.00	21.90	9.70	100.00
	Tree numbers	5,237,207	755,067	978,935	510,025	1,948,805	767,078	10,197,118
Solano	Canopy cover (m²)	22,432,582	2,512,457	2,957,672	1,513,465	9,749,575	7,126,917	46,292,667
	Canopy cover (%)	31.90	28.00	11.90	18.60	18.60	18.20	22.70
	Total urban land (m²)	70,221,400	8,982,670	24,876,820	8,122,500	52,485,950	39,073,260	203,762,600
	Total urban land (%)	34.50	4.40	12.20	4.00	25.80	19.20	100.00
	Tree numbers	1,143,067	128,024	150,710	77,120	496,796	363,157	2,358,874
Sonoma	Canopy cover (m²)	31,992,334	9,084,448	4,925,906	2,272,367	7,745,015	5,111,384	61,131,454
	Canopy cover (%)	41.10	37.30	18.10	28.50	32.10	25.50	33.70
	Total urban land (m²)	77,765,600	24,364,300	27,167,300	7,960,860	24,104,300	20,044,700	181,407,060
	Total urban land (%)	42.90	13.40	15.00	4.40	13.30	11.00	100.00
	Tree numbers	1,630,191	462,904	251,003	115,790	394,652	260,454	3,114,994
Bay Area total	Canopy cover (m²)	391,706,464	86,014,608	55,352,194	33,131,700	139,088,020	102,717,923	808,010,909
	Canopy cover (%)	40.30	27.10	14.70	24.30	24.00	25.30	29.00
	Total urban land (m²)	970,833,620	317,817,190	377,704,410	136,512,454	579,300,632	406,491,270	2,788,659,576
	Total urban land (%)	34.80	11.40	13.50	4.90	20.80	14.60	100.00
	Tree numbers	19,959,664	4,382,932	2,820,508	1,688,248	7,087,323	5,234,060	41,172,735

Appendix II. Resource units

Tables 21–25 present the resource units in engineering trems and in dollars per square meter of canopy cover for the benefits provided by trees in the nine counties of the study area.

Table 21—Resource units and their values for the East Bay

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units
	Resource units (engineering units)						
Hydrology	0.066	0.066	0.066	0.079	0.111	0.101	m^3/m^2
Property value	0.448	0.448	0.372	0.482	0.848	0.54	m^2/m^2
Ozone dep	0.002	0.002	0.002	0.002	0.003	0.003	kg/m^2
NOx dep	0.001	0.001	0.001	0.001	0.001	0.001	kg/m^2
PM_{10} dep	0.001	0.001	0.001	0.001	0.002	0.002	kg/m^2
SOx dep	0	0	0	0	0	0	kg/m^2
NOx avoided	0	0	0.001	0	0	0	kg/m^2
PM_{10} avoided	0	0	0	0	0	0	kg/m^2
SOx avoided	0	0	0	0	0	0	kg/m^2
VOC avoided	0	0	0	0	0	0	kg/m^2
BVOC	−0.006	−0.006	−0.008	−0.016	−0.034	−0.026	kg/m^2
Net VOCs	−0.006	−0.006	−0.008	−0.016	−0.034	−0.026	kg/m^2
Net air quality	−0.001	−0.001	−0.003	−0.011	−0.028	−0.02	kg/m^2
CO_2 sequestered	1.029	1.029	1.002	1.526	2.601	2.026	kg/m^2
CO_2 decomp	0.093	0.093	0.116	0.176	0.273	0.27	kg/m^2
CO_2 maint	0.016	0.016	0.015	0.016	0.024	0.02	kg/m^2
Net CO_2 sequestered	0.919	0.919	0.872	1.333	2.304	1.736	kg/m^2
CO_2 avoided	22.648	11.488	28.063	0	0	0	kg/m^2
Natural gas	2.339	0.974	11.992	0	0	0	$kBtu/m^2$
Electricity	1.371	0.685	1.861	0	0	0	kWh/m^2

Table 21, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units	
	Resource units (dollars per square meter of canopy cover)							
Hydrology	0.096	0.096	0.096	0.115	0.161	0.147	1.453	$/m^3
Property value	7.561	7.561	6.276	8.134	14.313	9.114	16.87	$/m^2
Ozone dep	0.004	0.004	0.005	0.005	0.006	0.006	2.16	$/kg
NOx dep	0.002	0.002	0.002	0.002	0.003	0.003	2.16	$/kg
PM_{10} dep	0.001	0.001	0.001	0.001	0.001	0.001	0.84	$/kg
SOx dep	0.0006	0.0006	0.0007	0.001	0.001	0.001	3.87	$/kg
NOx avoided	0.0008	0.0004	0.002	0	0	0	2.16	$/kg
PM_{10} avoided	0.0002	0.0001	0.0004	0	0	0	2.16	$/kg
SOx avoided	0.0003	0.0002	0	0	0	0	3.87	$/kg
VOC avoided	0	0	0.000	0	0	0	0.84	$/kg
BVOC	−0.005	−0.005	−0.007	−0.013	−0.029	−0.022	0.84	$/kg
Net VOCs	−0.005	−0.005	−0.007	−0.013	−0.029	−0.022	0.84	$/kg
Net air quality	0.004	0.004	0.003	−0.005	−0.017	−0.011		
CO_2 sequestered	0.003	0.003	0.003	0.005	0.009	0.007	0.00334	$/kg
CO_2 decomp	0	0	0	0.001	0.001	0.001	0.00334	$/kg
CO_2 maint	0	0	0	0	0	0	0.00334	$/kg
Net CO_2 sequestered	0.003	0.003	0.003	0.004	0.008	0.006	0.00334	$/kg
CO_2 avoided	0.076	0.038	0.094	0	0	0	0.00334	$/kg
Natural gas	0.04	0.017	0.207	0	0	0	0.017	$/kBtu
Electricity	0.292	0.146	0.397	0	0	0	0.21	$/kWh
Total	8.073	7.865	7.076	8.249	14.465	9.256		

Table 22—Resource units and their values for the North Bay

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units
	Resource units (engineering units)						
Hydrology	0.072	0.082	0.06	0.075	0.08	0.063	m^3/m^2
Property value	0.448	0.336	0.246	0.241	0	0.27	m^2/m^2
Ozone dep	0.003	0.003	0.003	0.003	0.004	0.003	kg/m^2
NOx dep	0.001	0.001	0.001	0.001	0.001	0.001	kg/m^2
PM_{10} dep	0.001	0.001	0.001	0.002	0.002	0.001	kg/m^2
SOx dep	0.0002	0.0002	0.0002	0.0002	0.0002	0.000	kg/m^2
NOx avoided	0.0011	0.0005	0.0009	0	0	0	kg/m^2
PM_{10} avoided	0.0003	0.0001	0.0002	0	0	0	kg/m^2
SOx avoided	0.0002	0.0001	0	0	0	0	kg/m^2
VOC avoided	0.0001	0	0.0001	0	0	0	kg/m^2
BVOC	−0.002	−0.001	−0.006	−0.005	−0.006	−0.003	kg/m^2
Net VOCs	−0.002	−0.001	−0.006	−0.005	−0.005	−0.002	kg/m^2
Net air quality	0.005	0.005	0.001	0.001	0.001	0.003	kg/m^2
CO_2 sequestered	0.829	0.812	0.766	1.395	1.528	0.759	kg/m^2
CO_2 decomp	0.17	0.162	0.124	0.276	0.297	0.155	kg/m^2
CO_2 maint	0.018	0.019	0.014	0.017	0.016	0.023	kg/m^2
Net CO_2 sequestered	0.641	0.631	0.627	1.102	1.215	0.581	kg/m^2
CO_2 avoided	44.741	22.606	33.557	0	0	0	kg/m^2
Natural gas	8.495	3.488	9.208	0	0	0	$kBtu/m^2$
Electricity	3.572	1.776	2.589	0	0	0	kWh/m^2

Table 22, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units	
	Resource units (dollars per square meter of canopy cover)							
Hydrology	0.104	0.119	0.087	0.109	0.117	0.091	1.453	$/m^3
Property value	8.238	6.179	4.514	4.432	0	4.965	18.38	$/m^2
Ozone dep	0.008	0.008	0.007	0.008	0.008	0.007	2.32	$/kg
NOx dep	0.002	0.002	0.002	0.002	0.002	0.002	2.32	$/kg
PM_{10} dep	0.001	0.001	0.001	0.001	0.002	0.001	0.96	$/kg
SOx dep	0.0006	0.0006	0.0006	0.0007	0.0007	0.0006	3.19	$/kg
NOx avoided	0.0026	0.0012	0.0022	0	0	0	2.32	$/kg
PM_{10} avoided	0.0007	0.0003	0.0005	0	0	0	2.32	$/kg
SOx avoided	0.0007	0.0003	0	0	0	0	3.19	$/kg
VOC avoided	0.000	0	0.000	0	0	0	0.96	$/kg
BVOC	−0.002	−0.001	−0.006	−0.005	−0.005	−0.002	0.96	$/kg
Net VOCs	−0.002	−0.001	−0.006	−0.005	−0.005	−0.002	0.96	$/kg
Net air quality	0.014	0.012	0.008	0.007	0.008	0.009		
CO_2 sequestered	0.003	0.003	0.003	0.005	0.005	0.003	0.00334	$/kg
CO_2 decomp	0.001	0.001	0	0.001	0.001	0.001	0.00334	$/kg
CO_2 maint	0	0	0	0	0	0	0.00334	$/kg
Net CO_2 sequestered	0.002	0.002	0.002	0.004	0.004	0.002	0.00334	$/kg
CO_2 avoided	0.149	0.076	0.112	0	0	0	0.00334	$/kg
Natural gas	0.147	0.06	0.159	0	0	0	0.017	$/kBtu
Electricity	0.761	0.379	0.552	0	0	0	0.21	$/kWh
Total	9.416	6.827	5.433	4.552	0.129	5.067		

Table 23—Resource units and their values for the South Bay

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units
	Resource units (engineering units)						
Hydrology	0.075	0.085	0.06	0.078	0.084	0.064	m^3/m^2
Property value	0.448	0.336	0.246	0.241	0	0.27	m^2/m^2
Ozone dep	0.003	0.003	0.003	0.003	0.003	0.003	kg/m^2
NOx dep	0.002	0.002	0.001	0.002	0.002	0.001	kg/m^2
PM_{10} dep	0.002	0.002	0.002	0.002	0.003	0.002	kg/m^2
SOx dep	0.0003	0.0003	0.0002	0.0003	0.0003	0.0003	kg/m^2
NOx avoided	0.0007	0.0004	0.0008	0	0	0	kg/m^2
PM_{10} avoided	0.0003	0.0001	0.0002	0	0	0	kg/m^2
SOx avoided	0.0002	0.0001	0	0	0	0	kg/m^2
VOC avoided	0.0001	0	0.0001	0	0	0	kg/m^2
BVOC	−0.002	−0.001	−0.006	−0.006	−0.006	−0.003	kg/m^2
Net VOCs	−0.002	−0.001	−0.006	−0.006	−0.006	−0.003	kg/m^2
Net air quality	0.006	0.006	0.001	0.002	0.002	0.004	kg/m^2
CO_2 sequestered	0.829	0.812	0.766	1.395	1.528	0.759	kg/m^2
CO_2 decomp	0.17	0.162	0.124	0.276	0.297	0.155	kg/m^2
CO_2 maint	0.018	0.019	0.014	0.017	0.016	0.023	kg/m^2
Net CO_2 sequestered	0.641	0.631	0.627	1.102	1.215	0.581	kg/m^2
CO_2 avoided	40.936	20.901	35.197	0	0	0	kg/m^2
Natural gas	0.194	0.098	3.451	0	0	0	$kBtu/m^2$
Electricity	3.49	1.767	3.07	0	0	0	kWh/m^2

Table 23, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units	
	Resource units (dollars per square meter of canopy cover)							
Hydrology	0.108	0.124	0.088	0.113	0.122	0.092	1.453	$/m^3
Property value	8.196	6.147	4.491	4.409	0	4.94	18.29	$/m^2
Ozone dep	0.014	0.014	0.012	0.015	0.016	0.013	4.74	$/kg
NOx dep	0.007	0.007	0.006	0.008	0.008	0.007	4.74	$/kg
PM_{10} dep	0.005	0.005	0.004	0.005	0.006	0.005	2.25	$/kg
SOx dep	0.0011	0.0011	0.001	0.0012	0.0013	0.0011	4.04	$/kg
NOx avoided	0.0033	0.0017	0.0037	0	0	0	4.74	$/kg
PM_{10} avoided	0.0013	0.0006	0.0012	0	0	0	4.74	$/kg
SOx avoided	0.0009	0.0004	0	0	0	0	4.04	$/kg
VOC avoided	0.0002	0.0001	0.0002	0	0	0	2.25	$/kg
BVOC	−0.005	−0.003	−0.014	−0.014	−0.014	−0.007	2.25	$/kg
Net VOCs	−0.005	−0.003	−0.013	−0.013	−0.014	−0.007	2.25	$/kg
Net air quality	0.028	0.027	0.015	0.016	0.017	0.019		
CO_2 sequestered	0.003	0.003	0.003	0.005	0.005	0.003	0.00334	$/kg
CO_2 decomp	0.001	0.001	0	0.001	0.001	0.001	0.00334	$/kg
CO_2 maint	0	0	0	0	0	0	0.00334	$/kg
Net CO_2 sequestered	0.002	0.002	0.002	0.004	0.004	0.002	0.00334	$/kg
CO_2 avoided	0.137	0.07	0.118	0	0	0	0.00334	$/kg
Natural gas	0.003	0.002	0.06	0	0	0	0.017	$/kBtu
Electricity	0.744	0.377	0.654	0	0	0	0.21	$/kWh
Total	9.218	6.748	5.427	4.542	0.143	5.053		

Table 24—Resource units and their values for the West Bay

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units
	Resource units (engineering units)						
Hydrology	0.152	0.152	0.181	0.185	0.178	0.167	m^3/m^2
Property value	0.448	0.336	0.246	0.241	0	0.27	m^2/m^2
Ozone dep	0.004	0.004	0.004	0.004	0.004	0.004	kg/m^2
NOx dep	0.002	0.002	0.002	0.002	0.002	0.002	kg/m^2
PM_{10} dep	0.003	0.003	0.003	0.003	0.003	0.003	kg/m^2
SOx dep	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	kg/m^2
NOx avoided	0.0002	0.0001	0.0004	0	0	0	kg/m^2
PM_{10} avoided	0.0001	0	0.0001	0	0	0	kg/m^2
SOx avoided	0	0	0	0	0	0	kg/m^2
VOC avoided	0	0	0	0	0	0	kg/m^2
BVOC	−0.002	−0.002	−0.002	−0.003	−0.004	−0.002	kg/m^2
Net VOCs	−0.002	−0.002	−0.002	−0.003	−0.004	−0.002	kg/m^2
Net air quality	0.006	0.006	0.007	0.006	0.005	0.006	kg/m^2
CO_2 sequestered	1.096	1.096	0.993	1.064	0.939	1.013	kg/m^2
CO_2 decomp	0.131	0.131	0.142	0.166	0.17	0.135	kg/m^2
CO_2 maint	0.023	0.023	0.018	0.017	0.019	0.02	kg/m^2
Net CO_2 sequestered	0.941	0.941	0.833	0.881	0.75	0.858	kg/m^2
CO_2 avoided	7.683	3.759	8.568	0	0	0	kg/m^2
Natural gas	0.751	0.341	4.571	0	0	0	$kBtu/m^2$
Electricity	0.563	0.274	0.623	0	0	0	kWh/m^2

Table 24, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units	
	Resource units (dollars per square meter of canopy cover)							
Hydrology	0.221	0.221	0.263	0.269	0.259	0.243	1.453	$/m^3
Property value	9.651	7.238	5.288	5.192	0	5.817	21.53	$/m^2
Ozone dep	0.005	0.005	0.005	0.005	0.005	0.005	1.43	$/kg
NOx dep	0.002	0.002	0.002	0.002	0.002	0.002	1.43	$/kg
PM_{10} dep	0.001	0.001	0.001	0.001	0.001	0.001	0.44	$/kg
SOx dep	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	3.89	$/kg
NOx avoided	0.0002	0.0001	0.0005	0	0	0	1.43	$/kg
PM_{10} avoided	0.0001	0	0.0001	0	0	0	1.43	$/kg
SOx avoided	0.0002	0.0001	0	0	0	0	3.89	$/kg
VOC avoided	0	0	0	0	0	0	0.44	$/kg
BVOC	−0.001	−0.001	−0.001	−0.001	−0.002	−0.001	0.44	$/kg
Net VOCs	−0.001	−0.001	−0.001	−0.001	−0.002	−0.001	0.44	$/kg
Net air quality	0.009	0.009	0.01	0.009	0.008	0.009		
CO_2 sequestered	0.004	0.004	0.003	0.004	0.003	0.003	0.00334	$/kg
CO_2 decomp	0	0	0	0.001	0.001	0	0.00334	$/kg
CO_2 maint	0	0	0	0	0	0	0.00334	$/kg
Net CO_2 sequestered	0.003	0.003	0.003	0.003	0.003	0.003	0.00334	$/kg
CO_2 avoided	0.026	0.013	0.029	0	0	0	0.00334	$/kg
Natural gas	0.013	0.006	0.079	0	0	0	0.017	$/kBtu
Electricity	0.12	0.058	0.133	0	0	0	0.21	$/kWh
Total	10.044	7.549	5.804	5.472	0.269	6.071		

Table 25—Resource units and their values for the Central Valley

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units
	Resource units (engineering units)						
Hydrology	0.066	0.076	0.052	0.069	0.075	0.055	m^3/m^2
Property value	0.448	0.336	0.246	0.241	0	0.27	m^2/m^2
Ozone dep	0.002	0.002	0.001	0.002	0.002	0.002	kg/m^2
NOx dep	0.001	0.001	0	0.001	0.001	0	kg/m^2
PM_{10} dep	0.001	0.002	0.001	0.002	0.002	0.001	kg/m^2
SOx dep	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	kg/m^2
NOx avoided	0.001	0.0005	0.0011	0	0	0	kg/m^2
PM_{10} avoided	0.0003	0.0002	0.0003	0	0	0	kg/m^2
SOx avoided	0.0002	0.0001	0	0	0	0	kg/m^2
VOC avoided	0.0001	0	0.0001	0	0	0	kg/m^2
BVOC	−0.002	−0.002	−0.007	−0.007	−0.007	−0.003	kg/m^2
Net VOCs	−0.002	−0.002	−0.007	−0.007	−0.007	−0.003	kg/m^2
Net air quality	0.003	0.003	−0.002	−0.002	−0.003	0	kg/m^2
CO_2 sequestered	0.829	0.812	0.766	1.395	1.528	0.759	kg/m^2
CO_2 decomp	0.17	0.162	0.124	0.276	0.297	0.155	kg/m^2
CO_2 maint	0.018	0.019	0.014	0.017	0.016	0.023	kg/m^2
Net CO_2 sequestered	0.641	0.631	0.627	1.102	1.215	0.581	kg/m^2
CO_2 avoided	48.329	24.234	34.992	0	0	0	kg/m^2
Natural gas	2.866	1.227	11.016	0	0	0	$kBtu/m^2$
Electricity	4.103	2.032	2.981	0	0	0	kWh/m^2

Table 25—Resource units and their values for the Central Valley

Benefit	Residential low	Residential high	Commercial / industrial	Institutional*	Open space	Transportation	Units	
	Resource units (dollars per square meter of canopy cover)							
Hydrology	0.095	0.111	0.076	0.1	0.109	0.081	1.453	$/m^3
Property value	6.461	4.846	3.54	3.476	0	3.894	14.42	$/m^2
Ozone dep	0.006	0.006	0.005	0.007	0.007	0.006	3.69	$/kg
NOx dep	0.002	0.002	0.002	0.002	0.002	0.002	3.69	$/kg
PM_{10} dep	0.002	0.003	0.002	0.003	0.003	0.002	1.69	$/kg
SOx dep	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	3.63	$/kg
NOx avoided	0.0035	0.0017	0.0041	0	0	0	3.69	$/kg
PM_{10} avoided	0.0012	0.0006	0.001	0	0	0	3.69	$/kg
SOx avoided	0.0009	0.0004	0	0	0	0	3.63	$/kg
VOC avoided	0.0002	0.0001	0.0001	0	0	0	1.69	$/kg
BVOC	−0.004	−0.003	−0.012	−0.011	−0.012	−0.006	1.69	$/kg
Net VOCs	−0.004	−0.003	−0.011	−0.011	−0.012	−0.005	1.69	$/kg
Net air quality	0.013	0.011	0.003	0.001	0.001	0.005		
CO_2 sequestered	0.003	0.003	0.003	0.005	0.005	0.003	0.00334	$/kg
CO_2 decomp	0.001	0.001	0	0.001	0.001	0.001	0.00334	$/kg
CO_2 maint	0	0	0	0	0	0	0.00334	$/kg
Net CO_2 sequestered	0.002	0.002	0.002	0.004	0.004	0.002	0.00334	$/kg
CO_2 avoided	0.161	0.081	0.117	0	0	0	0.00334	$/kg
Natural gas	0.049	0.021	0.187	0	0	0	0.017	$/kBtu
Electricity	0.875	0.433	0.635	0	0	0	0.21	$/kWh
Total	7.656	5.505	4.56	3.581	0.113	3.982		

Appendix III. Benefit tables

Tables 26–34 describe the environmental and other benefits in both engineering units and dollars for the nine studied counties.

Table 26—Benefits for Alameda County (existing canopy cover 23.4 percent)

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	Units
				Benefits (engineering units)				
Hydrology	3,538,648	1,353,000	606,845	511,552	2,462,443	1,492,530	9,965,018	m^3
Property value	23,958,391	6,745,676	2,406,920	1,593,108	0	4,326,737	39,030,833	m^2
Ozone dep	100,830	38,797	18,653	14,049	64,227	40,933	277,489	kg
NOx dep	41,286	16,396	7,269	5,914	27,307	17,426	115,599	kg
PM_{10} dep	63,614	22,944	11,410	8,462	39,512	24,618	170,561	kg
SOx dep	8,502	3,278	1,538	1,183	5,453	3,490	23,443	kg
NOx avoided	28,826	4,271	9,626	0	0	0	42,724	kg
PM_{10} avoided	9,088	1,342	2,030	0	0	0	12,459	kg
SOx avoided	6,872	1,014	41	0	0	0	7,927	kg
VOC avoided	2,588	383	711	0	0	0	3,682	kg
BVOC	−258,670	−103,508	−77,873	−94,196	−675,619	−350,213	−1,560,079	kg
Net VOCs	−256,082	−103,125	−77,162	−94,196	−675,619	−350,213	−1,556,397	kg
Net air quality	2,937	−15,083	−26,595	−64,587	−539,121	−263,746	−906,195	kg
CO_2 sequestered	52,439,538	20,179,155	9,153,158	9,952,810	56,622,085	28,830,315	177,177,061	kg
CO_2 decomp	6,713,892	2,351,449	1,331,922	1,475,557	7,706,642	4,777,479	24,356,940	kg
CO_2 maint	3,875,137	1,644,223	609,485	531,504	2,565,545	1,545,683	10,771,577	kg
Net CO_2 sequestered	41,850,509	16,183,482	7,211,751	7,945,750	46,349,898	22,507,153	142,048,543	kg
CO_2 avoided	55,068,437	10,465,928	8,882,309	0	0	0	74,416,674	kg
Natural gas	131,799,352	20,086,307	114,781,248	0	0	0	266,666,907	kBtu
Electricity	112,738,666	16,633,246	21,415,094	0	0	0	150,787,006	kWh

Table 26, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	% of total
				Benefits ($)				
Hydrology	5,141,466	1,965,837	881,714	743,258	3,577,798	2,168,566	14,478,639	2.10
Property value	390,150,554	112,033,716	38,899,464	26,287,765	0	71,096,019	638,467,518	92.50
Ozone dep	249,621	89,237	46,543	33,057	153,008	95,195	666,661	
NOx dep	99,355	37,163	17,515	13,685	63,871	39,786	271,374	
PM10 dep	69,364	21,996	12,634	8,477	40,401	24,079	176,951	
SOx dep	32,529	12,629	5,873	4,549	20,947	13,435	89,962	
NOx avoided	81,453	10,745	25,584	0	0	0	117,781	
PM10 avoided	26,136	3,420	5,531	0	0	0	35,087	
SOx avoided	25,839	3,866	159	0	0	0	29,864	
VOC avoided	3,167	401	805	0	0	0	4,373	
BVOC	−243,744	−89,781	−81,875	−84,687	−597,323	−302,052	−1,399,461	
Net VOCs	−240,577	−89,380	−81,070	−84,687	−597,323	−302,052	−1,395,088	
Net air quality	343,719	89,676	32,768	−24,919	−319,096	−129,557	−7,408	0.00
CO_2 sequestered	175,148	67,398	30,572	33,242	189,118	96,293	591,771	
CO_2 decomp	22,424	7,854	4,449	4,928	25,740	15,957	81,352	
CO_2 maint	12,943	5,492	2,036	1,775	8,569	5,163	35,977	
Net CO_2 sequestered	139,781	54,053	24,087	26,539	154,809	75,174	474,442	0.01
CO_2 avoided	183,929	34,956	29,667	0	0	0	248,552	0.00
Natural gas	2,264,657	346,025	1,972,415	0	0	0	4,583,097	0.70
Electricity	24,029,119	3,545,210	4,564,413	0	0	0	32,138,742	4.70
Total	422,253,225	118,069,473	46,404,529	27,032,643	3,413,510	73,210,202	690,383,581	
Percent benefit	61.20	17.10	6.70	3.90	0.50	10.60	100.00	
Benefits/tree ($)	155	115	93	80	3	90	104	

Table 27—Benefits for Contra Costa County (existing canopy cover 31.3 percent)

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	Units
				Benefits (engineering units)				
Hydrology	5,786,770	1,457,827	505,903	488,224	1,975,462	1,650,287	11,864,473	m^3
Property value	39,447,104	6,603,202	2,225,261	1,662,678	0	6,586,935	56,525,181	m^2
Ozone dep	146,913	34,250	14,699	12,909	50,132	46,028	304,931	kg
NOx dep	48,749	11,963	4,915	4,610	18,128	16,805	105,169	kg
PM_{10} dep	127,141	27,891	11,173	10,720	42,134	35,324	254,384	kg
SOx dep	12,175	2,825	1,241	1,053	4,064	3,832	25,189	kg
NOx avoided	82,292	7,978	9,626	0	0	0	99,896	kg
PM_{10} avoided	27,770	2,707	2,208	0	0	0	32,686	kg
SOx avoided	21,374	2,086	14	0	0	0	23,474	kg
VOC avoided	7,666	745	738	0	0	0	9,149	kg
BVOC	−240,066	−47,650	−65,984	−57,033	−264,472	−226,366	−901,571	kg
Net VOCs	−232,400	−46,904	−65,246	−57,033	−264,472	−226,366	−892,422	kg
Net air quality	234,015	42,795	−21,369	−27,741	−150,014	−124,378	−46,692	kg
CO_2 sequestered	74,488,159	16,857,745	7,510,845	9,787,651	41,501,304	26,715,353	176,861,057	kg
CO_2 decomp	14,486,738	2,975,913	1,165,753	1,826,774	7,484,031	4,912,880	32,852,090	kg
CO_2 maint	2,158,594	665,255	291,905	210,447	784,084	1,137,744	5,248,028	kg
Net CO_2 sequestered	57,842,828	13,216,577	6,053,187	7,750,430	33,233,189	20,664,728	138,760,939	kg
CO_2 avoided	90,669,294	10,244,879	8,211,927	0	0	0	109,126,100	kg
Natural gas	247,606,810	23,044,126	102,192,174	0	0	0	372,843,110	kBtu
Electricity	351,347,629	34,296,408	24,301,912	0	0	0	409,945,949	kWh

Table 27, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	% of total
				Benefits ($)				
Hydrology	8,407,867	2,118,144	735,050	709,364	2,870,241	2,397,779	17,238,445	1.80
Property value	577,111,429	98,638,825	33,541,934	24,715,259	0	99,254,437	833,261,885	88.10
Ozone dep	518,904	113,789	46,476	43,406	170,167	142,317	1,035,059	
NOx dep	169,870	38,697	14,894	15,180	60,390	49,932	348,964	
PM_{10} dep	207,175	43,127	16,537	16,771	66,411	50,966	400,986	
SOx dep	44,552	10,434	4,609	3,882	14,968	14,295	92,741	
NOx avoided	298,830	28,258	32,053	0	0	0	359,142	
PM_{10} avoided	101,033	9,627	7,465	0	0	0	118,125	
SOx avoided	77,841	7,623	55	0	0	0	85,520	
VOC avoided	12,695	1,199	1,107	0	0	0	15,002	
BVOC	−368,558	−60,612	−94,041	−79,524	−350,706	−239,738	−1,193,178	
Net VOCs	−355,863	−59,413	−92,933	−79,524	−350,706	−239,738	−1,178,176	
Net air quality	1,062,344	192,142	29,157	−285	−38,770	17,772	1,262,360	0.10
CO_2 sequestered	248,790	56,305	25,086	32,691	138,614	89,229	590,716	
CO_2 decomp	48,386	9,940	3,894	6,101	24,997	16,409	109,726	
CO_2 maint	7,210	2,222	975	703	2,619	3,800	17,528	
Net CO_2 sequestered	193,195	44,143	20,218	25,886	110,999	69,020	463,462	0.00
CO_2 avoided	302,835	34,218	27,428	0	0	0	364,481	0.00
Natural gas	4,205,605	392,133	1,742,316	0	0	0	6,340,054	0.70
Electricity	74,886,234	7,309,936	5,179,709	0	0	0	87,375,880	9.20
Total	666,169,509	108,729,541	41,275,813	25,450,225	2,942,470	101,739,008	946,306,566	
Percent benefit	70.40	11.50	4.40	2.70	0.30	10.80	100.00	
Benefits/tree ($)	149	109	89	72	2	82	107	

Table 28—Benefits for Marin County (existing canopy cover 46.8 percent)

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	Units
	Benefits (engineering units)							
Hydrology	3,836,097	483,645	416,274	22,070	1,398,750	1,161,296	7,318,132	m^3
Property value	17,010,383	1,520,132	1,066,277	70,695	0	3,298,301	22,965,788	m^2
Ozone dep	128,114	15,439	14,054	1,023	41,840	40,145	240,613	kg
NOx dep	43,825	5,249	4,541	282	14,831	13,375	82,103	kg
PM_{10} dep	70,595	8,442	7,213	444	24,070	21,468	132,232	kg
SOx dep	9,273	1,110	975	62	3,112	2,839	17,370	kg
NOx avoided	29,448	1,625	3,377	0	0	0	34,450	kg
PM_{10} avoided	8,236	475	799	0	0	0	9,510	kg
SOx avoided	5,976	350	0	0	0	0	6,326	kg
VOC avoided	2,443	138	258	0	0	0	2,839	kg
BVOC	−78,824	−7,668	−20,062	−1,527	−56,712	−31,064	−195,855	kg
Net VOCs	−76,381	−7,530	−19,803	−1,527	−56,712	−31,064	−193,017	kg
Net air quality	219,084	25,160	11,155	284	27,141	46,764	329,587	kg
CO_2 sequestered	35,136,652	4,125,478	3,618,688	409,186	15,174,951	10,229,281	68,694,236	kg
CO_2 decomp	5,913,032	684,539	562,173	81,005	2,889,929	1,818,754	11,949,432	kg
CO_2 maint	767,395	92,732	67,002	4,947	204,091	267,803	1,403,970	kg
Net CO_2 sequestered	28,456,225	3,348,206	2,989,514	323,234	12,080,932	8,142,724	55,340,834	kg
CO_2 avoided	39,098,419	2,358,488	3,934,905	0	0	0	45,391,812	kg
Natural gas	216,769,461	10,761,750	33,979,425	0	0	0	261,510,636	kBtu
Electricity	96,136,670	5,640,280	8,695,582	0	0	0	110,472,532	kWh

Table 28, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	% of total
				Benefits ($)				
Hydrology	5,573,644	702,711	604,824	32,066	2,032,309	1,687,302	10,632,855	2.20
Property value	332,107,782	29,631,310	20,603,070	1,299,522	0	63,841,693	447,483,377	91.80
Ozone dep	254,633	30,884	28,542	2,377	82,454	81,341	480,231	
NOx dep	81,701	9,863	8,621	656	27,549	25,484	153,874	
PM_{10} dep	48,291	5,846	5,052	426	16,414	15,187	91,215	
SOx dep	32,793	3,912	3,419	197	11,032	9,951	61,304	
NOx avoided	66,481	3,679	7,412	0	0	0	77,572	
PM_{10} avoided	18,453	1,067	1,768	0	0	0	21,288	
SOx avoided	19,480	1,139	0	0	0	0	20,619	
VOC avoided	2,255	128	232	0	0	0	2,614	
BVOC	−60,799	−5,639	−18,124	−1,464	−45,331	−24,936	−156,294	
Net VOCs	−58,544	−5,512	−17,893	−1,464	−45,331	−24,936	−153,680	
Net air quality	463,287	50,879	36,921	2,192	92,117	107,027	752,422	0.20
CO_2 sequestered	117,356	13,779	12,086	1,367	50,684	34,166	229,439	
CO_2 decomp	19,750	2,286	1,878	271	9,652	6,075	39,911	
CO_2 maint	2,563	310	224	17	682	894	4,689	
Net CO_2 sequestered	95,044	11,183	9,985	1,080	40,350	27,197	184,838	0.00
CO_2 avoided	130,589	7,877	13,143	0	0	0	151,609	0.00
Natural gas	3,742,871	185,819	586,709	0	0	0	4,515,399	0.90
Electricity	20,490,570	1,202,169	1,853,376	0	0	0	23,546,115	4.80
Total	362,603,787	31,791,948	23,708,027	1,334,860	2,164,775	65,663,218	487,266,615	
Percent benefit	74.40	6.50	4.90	0.30	0.40	13.50	100.00	
Benefits/tree ($)	187	138	107	89	4	106	135	

Table 29—Benefits for Napa County (existing canopy cover 34.1 percent)

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	Units
				Benefits (engineering units)				
Hydrology	721,036	184,754	33,004	59,005	245,446	260,667	1,503,913	m^3
Property value	4,494,999	755,571	135,671	189,006	0	1,120,560	6,695,808	m^2
Ozone dep	33,089	7,556	1,712	2,734	10,917	13,156	69,164	kg
NOx dep	8,815	2,022	431	755	3,060	3,494	18,577	kg
PM_{10} dep	13,731	3,147	655	1,188	4,834	5,431	28,986	kg
SOx dep	1,947	445	97	165	665	770	4,089	kg
NOx avoided	11,291	1,162	524	0	0	0	12,977	kg
PM_{10} avoided	3,093	332	127	0	0	0	3,552	kg
SOx avoided	2,243	244	0	0	0	0	2,488	kg
VOC avoided	942	99	41	0	0	0	1,083	kg
BVOC	−20,839	−3,347	−3,250	−4,082	−16,943	−10,671	−59,132	kg
Net VOCs	−19,896	−3,248	−3,209	−4,082	−16,943	−10,671	−58,049	kg
Net air quality	54,313	11,662	338	759	2,533	12,180	81,785	kg
CO_2 sequestered	8,314,450	1,825,699	422,970	1,093,982	4,659,580	3,149,908	19,466,589	kg
CO_2 decomp	1,701,002	364,559	68,663	216,571	905,156	644,088	3,900,038	kg
CO_2 maint	184,181	42,449	7,820	13,226	49,278	94,847	391,800	kg
Net CO_2 sequestered	6,429,267	1,418,691	346,488	864,186	3,705,146	2,410,974	15,174,752	kg
CO_2 avoided	10,331,769	1,172,269	500,671	0	0	0	12,004,709	kg
Natural gas	85,540,826	7,841,496	5,087,779	0	0	0	98,470,101	kBtu
Electricity	36,618,836	3,992,867	1,430,481	0	0	0	42,042,183	kWh

Table 29, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	% of total
				Benefits ($)				
Hydrology	1,047,627	268,438	47,954	85,732	356,621	378,735	2,185,106	1.60
Property value	82,627,931	13,889,048	2,493,935	3,474,349	0	20,598,356	123,083,619	90.30
Ozone dep	76,908	17,563	3,980	6,355	25,374	30,577	160,757	
NOx dep	20,489	4,700	1,002	1,754	7,111	8,122	43,179	
PM_{10} dep	13,163	3,017	628	1,139	4,634	5,206	27,787	
SOx dep	6,220	1,421	310	526	2,125	2,461	13,063	
NOx avoided	26,244	2,702	1,217	0	0	0	30,163	
PM_{10} avoided	7,188	772	295	0	0	0	8,255	
SOx avoided	7,166	780	0	0	0	0	7,946	
VOC avoided	904	95	39	0	0	0	1,038	
BVOC	−19,977	−3,208	−3,115	−3,914	−16,242	−10,229	−56,686	
Net VOCs	−19,073	−3,113	−3,076	−3,914	−16,242	−10,229	−55,648	
Net air quality	138,304	27,842	4,357	5,860	23,003	36,136	235,502	0.20
CO_2 sequestered	27,770	6,098	1,413	3,654	15,563	10,521	65,018	
CO_2 decomp	5,681	1,218	229	723	3,023	2,151	13,026	
CO_2 maint	615	142	26	44	165	317	1,309	
Net CO_2 sequestered	21,474	4,738	1,157	2,886	12,375	8,053	50,684	0.00
CO_2 avoided	34,508	3,915	1,672	0	0	0	40,096	0.00
Natural gas	1,476,999	135,396	87,849	0	0	0	1,700,243	1.20
Electricity	7,804,939	851,040	304,893	0	0	0	8,960,871	6.60
Total	93,151,781	15,180,418	2,941,817	3,568,827	391,999	21,021,280	136,256,121	
Percent benefit	68.40	11.10	2.20	2.60	0.30	15.40	100.00	
Benefits/tree ($)	182	133	104	89	3	99	128	

Table 30—Benefits for San Francisco County (existing canopy cover 16.1 percent)

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	Units
				Benefits (engineering units)				
Hydrology	88,159	784,065	102,606	182,322	539,867	1,361,807	3,058,825	m^3
Property value	259,169	1,728,745	139,318	237,506	0	2,198,856	4,563,594	m^2
Ozone dep	2,030	18,051	2,020	3,496	10,761	28,885	65,242	kg
NOx dep	948	8,436	947	1,636	5,035	13,525	30,528	kg
PM_{10} dep	1,575	14,012	1,577	2,720	8,370	22,489	50,743	kg
SOx dep	192	1,711	192	332	1,022	2,745	6,194	kg
NOx avoided	92	357	214	0	0	0	663	kg
PM_{10} avoided	32	137	43	0	0	0	213	kg
SOx avoided	24	102	0	0	0	0	126	kg
VOC avoided	7	28	14	0	0	0	49	kg
BVOC	−1,200	−10,672	−937	−2,535	−11,353	−20,194	−46,892	kg
Net VOCs	−1,193	−10,644	−923	−2,535	−11,353	−20,194	−46,843	kg
Net air quality	3,701	32,161	4,070	5,650	13,835	47,448	106,865	kg
CO_2 sequestered	633,863	5,637,443	563,307	1,047,956	2,848,142	8,247,691	18,978,403	kg
CO_2 decomp	76,031	676,203	80,378	163,399	515,607	1,097,553	2,609,172	kg
CO_2 maint	13,581	120,784	10,459	16,790	58,482	161,575	381,670	kg
Net CO_2 sequestered	544,252	4,840,456	472,471	867,767	2,274,053	6,988,563	15,987,561	kg
CO_2 avoided	595,701	2,682,151	514,127	0	0	0	3,791,978	kg
Natural gas	433,598	1,753,938	2,593,561	0	0	0	4,781,097	kBtu
Electricity	326,141	1,410,975	353,371	0	0	0	2,090,486	kWh

Table 30, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	% of total
				Benefits ($)				
Hydrology	128,090	1,139,204	149,081	264,903	784,398	1,978,633	4,444,309	4.30
Property value	5,580,973	37,226,967	3,000,080	5,114,487	0	47,350,372	98,272,878	95.00
Ozone dep	2,903	25,817	2,888	5,001	15,391	41,311	93,310	
NOx dep	1,357	12,065	1,355	2,340	7,202	19,343	43,661	
PM_{10} dep	695	6,180	695	1,200	3,692	9,919	22,382	
SOx dep	748	6,652	748	1,291	3,972	10,672	24,083	
NOx avoided	132	510	306	0	0	0	948	
PM_{10} avoided	46	196	62	0	0	0	305	
SOx avoided	92	397	0	0	0	0	488	
VOC avoided	3	12	6	0	0	0	22	
BVOC	−529	−4,707	−413	−1,118	−5,008	−8,907	−20,684	
Net VOCs	−526	−4,695	−407	−1,118	−5,008	−8,907	−20,662	
Net air quality	5,446	47,121	5,647	8,714	25,249	72,339	164,516	0.20
CO_2 sequestered	2,117	18,829	1,881	3,500	9,513	27,547	63,388	
CO_2 decomp	254	2,259	268	546	1,722	3,666	8,715	
CO_2 maint	45	403	35	56	195	540	1,275	
Net CO_2 sequestered	1,818	16,167	1,578	2,898	7,595	23,342	53,398	0.10
CO_2 avoided	1,990	8,958	1,717	0	0	0	12,665	0.00
Natural gas	7,487	30,285	44,782	0	0	0	82,553	0.10
Electricity	69,514	300,735	75,317	0	0	0	445,566	0.40
Total	5,795,317	38,769,437	3,278,203	5,391,002	817,242	49,424,686	103,475,887	
Percent benefit	5.60	37.50	3.20	5.20	0.80	47.80	100.00	
Benefits/tree ($)	197	148	113	107	5	119	110	

Table 31—Benefits for San Mateo County (existing canopy cover 31.7 percent)

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	Units
				Benefits (engineering units)				
Hydrology	6,777,984	1,215,317	710,836	697,670	2,999,149	1,760,263	14,161,219	m^3
Property value	19,925,920	2,679,592	965,168	908,840	0	2,842,226	27,321,746	m^2
Ozone dep	156,043	27,979	13,991	13,379	59,781	37,336	308,510	kg
NOx dep	72,923	13,075	6,562	6,262	27,973	17,482	144,278	kg
PM_{10} dep	121,128	21,719	10,922	10,410	46,497	29,069	239,744	kg
SOx dep	14,789	2,652	1,333	1,271	5,676	3,548	29,268	kg
NOx avoided	7,100	553	1,482	0	0	0	9,135	kg
PM_{10} avoided	2,495	213	301	0	0	0	3,009	kg
SOx avoided	1,817	158	0	0	0	0	1,975	kg
VOC avoided	543	44	95	0	0	0	681	kg
BVOC	−92,260	−16,543	−6,492	−9,702	−63,070	−26,103	−214,169	kg
Net VOCs	−91,717	−16,499	−6,397	−9,702	−63,070	−26,103	−213,488	kg
Net air quality	284,578	49,850	28,194	21,619	76,857	61,332	522,431	kg
CO_2 sequestered	48,733,867	8,738,157	3,902,492	4,010,101	15,822,426	10,660,911	91,867,953	kg
CO_2 decomp	5,845,559	1,048,130	556,843	625,262	2,864,380	1,418,690	12,358,863	kg
CO_2 maint	1,044,135	187,217	72,456	64,250	324,886	208,851	1,901,795	kg
Net CO_2 sequestered	41,844,173	7,502,811	3,273,194	3,320,589	12,633,160	9,033,370	77,607,296	kg
CO_2 avoided	45,799,791	4,157,391	3,561,779	0	0	0	53,518,961	kg
Natural gas	33,336,655	2,718,641	17,967,735	0	0	0	54,023,030	kBtu
Electricity	25,074,980	2,187,041	2,448,091	0	0	0	29,710,112	kWh

Table 31, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	% of total
				Benefits ($)				
Hydrology	9,848,048	1,765,790	1,032,806	1,013,677	4,357,604	2,557,568	20,575,494	3.30
Property value	429,086,737	57,702,595	20,784,022	19,571,053	0	61,204,777	588,349,184	95.30
Ozone dep	223,176	40,016	20,010	19,135	85,500	53,399	441,237	
NOx dep	104,296	18,701	9,386	8,956	40,008	25,003	206,349	
PM_{10} dep	53,428	9,580	4,818	4,592	20,509	12,822	105,748	
SOx dep	57,504	10,311	5,181	4,940	22,068	13,795	113,799	
NOx avoided	10,154	790	2,120	0	0	0	13,064	
PM_{10} avoided	3,568	304	431	0	0	0	4,303	
SOx avoided	7,064	615	0	0	0	0	7,678	
VOC avoided	239	19	42	0	0	0	300	
BVOC	−40,695	−7,297	−2,863	−4,280	−27,819	−11,514	−94,467	
Net VOCs	−40,455	−7,277	−2,822	−4,280	−27,819	−11,514	−94,167	
Net air quality	418,735	73,039	39,124	33,344	140,266	93,504	798,012	0.10
CO_2 sequestered	162,771	29,185	13,034	13,394	52,847	35,607	306,839	
CO_2 decomp	19,524	3,501	1,860	2,088	9,567	4,738	41,279	
CO_2 maint	3,487	625	242	215	1,085	698	6,352	
Net CO_2 sequestered	139,760	25,059	10,932	11,091	42,195	30,171	259,208	0.00
CO_2 avoided	152,971	13,886	11,896	0	0	0	178,753	0.00
Natural gas	575,611	46,942	310,242	0	0	0	932,794	0.20
Electricity	5,344,481	466,146	521,786	0	0	0	6,332,413	1.00
Total	445,566,342	60,093,457	22,710,809	20,629,165	4,540,065	63,886,021	617,425,858	
Percent benefit	72.20	9.70	3.70	3.30	0.70	10.30	100.00	
Benefits/tree ($)	197	148	113	107	5	119	138	

Table 32—Benefits for Santa Clara County (existing canopy cover 28.9 percent)

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	Units
				Benefits (engineering units)				
Hydrology	7,662,457	1,262,301	1,156,998	776,528	3,203,407	956,573	15,018,263	m^3
Property value	46,062,446	4,980,743	4,717,439	2,413,093	0	4,066,262	62,239,983	m^2
Ozone dep	295,713	43,933	49,009	31,776	126,812	41,688	588,932	kg
NOx dep	156,532	23,394	25,457	17,089	68,594	22,283	313,348	kg
PM_{10} dep	225,623	33,459	37,010	24,259	96,987	31,353	448,690	kg
SOx dep	28,418	4,167	4,746	3,011	11,956	3,993	56,290	kg
NOx avoided	71,930	5,213	14,959	0	0	0	92,102	kg
PM_{10} avoided	27,470	2,002	4,746	0	0	0	34,218	kg
SOx avoided	21,753	1,587	0	0	0	0	23,340	kg
VOC avoided	7,187	523	1,347	0	0	0	9,057	kg
BVOC	−224,085	−20,555	−115,580	−60,197	−244,746	−44,721	−709,883	kg
Net VOCs	−218,305	−19,729	−114,463	−59,641	−242,613	−43,895	−698,646	kg
Net air quality	610,542	93,723	21,694	15,938	59,603	54,595	856,095	kg
CO_2 sequestered	85,202,227	12,035,052	14,707,130	13,967,165	58,421,733	11,430,311	195,763,618	kg
CO_2 decomp	17,430,995	2,403,183	2,387,479	2,765,016	11,348,826	2,337,250	38,672,749	kg
CO_2 maint	1,887,398	279,823	271,896	168,857	617,845	344,177	3,569,996	kg
Net CO_2 sequestered	65,883,834	9,352,046	12,047,755	11,033,292	46,455,062	8,748,884	153,520,873	kg
CO_2 avoided	105,874,677	7,727,631	17,408,862	0	0	0	131,011,170	kg
Natural gas	19,963,643	1,445,953	66,301,268	0	0	0	87,710,864	kBtu
Electricity	358,724,567	26,182,757	58,984,702	0	0	0	443,892,026	kWh

Table 32, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	% of total
				Benefits ($)				
Hydrology	11,133,141	1,834,055	1,681,056	1,128,254	4,654,379	1,389,849	21,820,733	1.40
Property value	1,044,545,400	112,946,935	106,976,054	54,721,049	0	92,209,513	1,411,398,951	92.00
Ozone dep	1,401,427	208,204	232,260	150,593	600,983	197,568	2,791,035	
NOx dep	741,830	110,867	120,643	80,985	325,075	105,601	1,485,002	
PM_{10} dep	506,978	75,182	83,163	54,510	217,930	70,450	1,008,213	
SOx dep	114,707	16,818	19,158	12,152	48,258	16,118	227,210	
NOx avoided	340,887	24,707	70,893	0	0	0	436,487	
PM_{10} avoided	130,185	9,489	22,491	0	0	0	162,164	
SOx avoided	87,803	6,408	0	0	0	0	94,211	
VOC avoided	16,150	1,174	3,028	0	0	0	20,352	
BVOC	−503,522	−46,187	−259,711	−135,262	−549,947	−100,490	−1,595,118	
Net VOCs	−490,535	−44,332	−257,199	−134,014	−545,155	−98,632	−1,569,868	
Net air quality	2,836,446	406,663	291,925	162,977	642,299	289,247	4,629,557	0.30
CO_2 sequestered	284,575	40,197	49,122	46,650	195,129	38,177	653,850	
CO_2 decomp	58,220	8,027	7,974	9,235	37,905	7,806	129,167	
CO_2 maint	6,304	935	908	564	2,064	1,150	11,924	
Net CO_2 sequestered	220,052	31,236	40,240	36,851	155,160	29,221	512,760	0.00
CO_2 avoided	353,621	25,810	58,146	0	0	0	437,577	0.00
Natural gas	344,704	24,967	1,144,797	0	0	0	1,514,468	0.10
Electricity	76,458,554	5,580,593	12,571,999	0	0	0	94,611,146	6.20
Total	1,135,891,917	120,850,259	122,764,217	56,049,131	5,451,838	93,917,830	1,534,925,193	
Percent benefit	74.00	7.90	8.00	3.70	0.40	6.10	100.00	
Benefits/tree ($)	217	160	125	110	3	122	151	

Table 33—Benefits for Solano County (existing canopy cover 22.7 percent)

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	Units
				Benefits (engineering units)				
Hydrology	1,475,837	188,150	159,031	106,834	785,668	428,985	3,144,504	m^3
Property value	10,053,540	844,500	726,265	364,878	0	1,925,085	13,914,267	m^2
Ozone dep	37,932	4,333	4,517	2,821	19,970	12,055	81,628	kg
NOx dep	12,917	1,478	1,405	1,001	7,297	4,077	28,175	kg
PM_{10} dep	31,830	3,636	3,716	2,365	16,516	10,139	68,202	kg
SOx dep	3,150	356	385	230	1,623	993	6,737	kg
NOx avoided	20,081	1,069	3,222	0	0	0	24,372	kg
PM_{10} avoided	6,750	364	757	0	0	0	7,871	kg
SOx avoided	5,190	281	2	0	0	0	5,473	kg
VOC avoided	1,867	100	250	0	0	0	2,216	kg
BVOC	−65,942	−5,408	−20,872	−12,238	−111,596	−39,852	−255,908	kg
Net VOCs	−64,076	−5,308	−20,622	−12,238	−111,596	−39,852	−253,692	kg
Net air quality	53,773	6,209	−6,619	−5,820	−66,189	−12,587	−31,234	kg
CO_2 sequestered	19,287,663	2,118,977	2,346,385	2,143,874	16,596,256	6,335,098	48,828,253	kg
CO_2 decomp	3,604,214	389,212	373,229	402,822	2,946,431	1,233,452	8,949,360	kg
CO_2 maint	658,249	73,013	65,314	43,862	341,276	228,304	1,410,019	kg
Net CO_2 sequestered	15,025,199	1,656,751	1,907,842	1,697,190	13,308,549	4,873,342	38,468,873	kg
CO_2 avoided	23,108,094	1,310,243	2,680,150	0	0	0	27,098,487	kg
Natural gas	62,321,779	2,990,394	32,919,696	0	0	0	98,231,869	kBtu
Electricity	85,301,156	4,616,483	8,428,181	0	0	0	98,345,821	kWh

Table 33, cont

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	% of total
				Benefits ($)				
Hydrology	2,144,312	273,372	231,063	155,224	1,141,533	623,292	4,568,796	2.00
Property value	148,754,622	12,474,213	10,680,066	5,405,469	0	28,237,876	205,552,247	88.10
Ozone dep	129,485	14,891	15,549	9,586	66,582	41,370	277,462	
NOx dep	43,132	4,979	4,718	3,337	23,807	13,681	93,654	
PM_{10} dep	50,420	5,792	5,933	3,734	25,627	16,122	107,628	
SOx dep	11,585	1,310	1,414	846	5,995	3,650	24,800	
NOx avoided	71,942	3,841	11,388	0	0	0	87,171	
PM_{10} avoided	24,264	1,311	2,696	0	0	0	28,271	
SOx avoided	18,935	1,024	8	0	0	0	19,967	
VOC avoided	3,044	164	402	0	0	0	3,609	
BVOC	−94,770	−7,403	−32,716	−17,392	−142,449	−51,193	−345,923	
Net VOCs	−91,726	−7,240	−32,314	−17,392	−142,449	−51,193	−342,314	
Net air quality	258,039	25,907	9,390	111	−20,438	23,630	296,639	0.10
CO_2 sequestered	64,421	7,077	7,837	7,161	55,431	21,159	163,086	
CO_2 decomp	12,038	1,300	1,247	1,345	9,841	4,120	29,891	
CO_2 maint	2,199	244	218	147	1,140	763	4,709	
Net CO_2 sequestered	50,184	5,534	6,372	5,669	44,451	16,277	128,486	0.10
CO_2 avoided	77,181	4,376	8,952	0	0	0	90,509	0.00
Natural gas	1,059,634	50,833	559,685	0	0	0	1,670,152	0.70
Electricity	18,181,088	983,957	1,796,383	0	0	0	20,961,428	9.00
Total	170,525,060	13,818,193	13,291,911	5,566,473	1,165,546	28,901,075	233,268,257	
Percent benefit	73.10	5.90	5.70	2.40	0.50	12.40	100.00	
Benefits/tree ($)	149	108	88	72	2	80	99	

Table 34—Benefits for Sonoma County (existing canopy cover 33.7 percent)

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	Units
				Benefits (engineering units)				
Hydrology	2,299,921	746,653	294,248	171,029	623,205	321,172	4,456,228	m^3
Property value	14,337,904	3,053,511	1,209,570	547,840	0	1,380,660	20,529,485	m^2
Ozone dep	105,546	30,538	15,266	7,925	27,719	16,209	203,203	kg
NOx dep	28,118	8,173	3,845	2,188	7,768	4,305	54,398	kg
PM_{10} dep	43,799	12,719	5,842	3,443	12,275	6,691	84,768	kg
SOx dep	6,211	1,797	866	478	1,689	949	11,991	kg
NOx avoided	36,016	4,698	4,669	0	0	0	45,383	kg
PM_{10} avoided	9,865	1,343	1,131	0	0	0	12,338	kg
SOx avoided	7,156	987	0	0	0	0	8,143	kg
VOC avoided	3,006	401	367	0	0	0	3,774	kg
BVOC	−66,471	−13,526	−28,974	−11,833	−43,020	−13,148	−176,971	kg
Net VOCs	−63,464	−13,125	−28,606	−11,833	−43,020	−13,148	−173,197	kg
Net air quality	173,246	47,129	3,012	2,200	6,432	15,007	247,026	kg
CO_2 sequestered	26,520,983	7,378,250	3,770,968	3,170,937	11,830,981	3,881,051	56,553,170	kg
CO_2 decomp	5,425,764	1,473,304	612,159	627,736	2,298,250	793,590	11,230,803	kg
CO_2 maint	587,492	171,549	69,715	38,335	125,120	116,862	1,109,074	kg
Net CO_2 sequestered	20,507,728	5,733,398	3,089,093	2,504,866	9,407,611	2,970,599	44,213,294	kg
CO_2 avoided	32,955,718	4,737,528	4,463,703	0	0	0	42,156,948	kg
Natural gas	272,853,491	31,690,072	45,359,829	0	0	0	349,903,392	kBtu
Electricity	116,804,777	16,136,492	12,753,377	0	0	0	145,694,646	kWh

Table 34, cont.

Benefit	Residential low	Residential high	Commercial / industrial	Institutional	Open space	Transportation	Total	% of total
				Benefits ($)				
Hydrology	3,341,663	1,084,847	427,527	248,496	905,483	466,646	6,474,661	1.50
Property value	263,562,094	56,130,228	22,234,554	10,070,492	0	25,379,555	377,376,923	89.40
Ozone dep	245,317	70,979	35,482	18,419	64,427	37,674	472,297	
NOx dep	65,355	18,996	8,936	5,085	18,056	10,007	126,435	
PM_{10} dep	41,987	12,193	5,600	3,300	11,767	6,415	81,261	
SOx dep	19,839	5,742	2,767	1,526	5,396	3,032	38,302	
NOx avoided	83,710	10,919	10,853	0	0	0	105,482	
PM_{10} avoided	22,929	3,120	2,629	0	0	0	28,678	
SOx avoided	22,858	3,153	0	0	0	0	26,010	
VOC avoided	2,882	384	352	0	0	0	3,618	
BVOC	−63,721	−12,967	−27,775	−11,344	−41,240	−12,604	−169,650	
Net VOCs	−60,839	−12,583	−27,423	−11,344	−41,240	−12,604	−166,032	
Net air quality	441,155	112,519	38,843	16,986	58,406	44,524	712,433	0.20
CO_2 sequestered	88,580	24,643	12,595	10,591	39,515	12,963	188,888	
CO_2 decomp	18,122	4,921	2,045	2,097	7,676	2,651	37,511	
CO_2 maint	1,962	573	233	128	418	390	3,704	
Net CO_2 sequestered	68,496	19,150	10,318	8,366	31,421	9,922	147,672	0.00
CO_2 avoided	110,072	15,823	14,909	0	0	0	140,804	0.00
Natural gas	4,711,251	547,180	783,210	0	0	0	6,041,641	1.40
Electricity	24,895,770	3,439,332	2,718,255	0	0	0	31,053,357	7.40
Total	297,130,501	61,349,079	26,227,615	10,344,340	995,310	25,900,646	421,947,491	
Percent benefit	70.40	14.50	6.20	2.50	0.20	6.10	100.00	
Benefits/tree ($)	182	133	104	89	3	99	135	

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