International Environmental Modelling and Software Society (iEMSs)
7th Intl. Congress on Env. Modelling and Software, San Diego, CA, USA,
Daniel P. Ames, Nigel W.T. Quinn and Andrea E. Rizzoli (Eds.)
http://www.iemss.org/society/index.php/iemss-2014-proceedings

ecoSmart Landscapes: A Versatile SaaS Platform for Green Infrastructure Applications in Urban Environments

E. Gregory McPherson[a], Qingfu Xiao[b], Joe Purohit[c], Mark Dietenberger[d], Charles R. Boardman[d], Jim Simpson[a], and Paula Peper[a]

[a]*USDA Forest Service, Pacific Southwest Research Station, Davis, CA, (gmcpherson@fs.fed.us)*
[b]*Department of Land, Air and Water Resources, UC Davis, Davis, CA, (qxiao@ucdavis.edu)*
[c]*EcoLayers, Inc., San Diego, CA, (joe@ecolayers.com)*
[d]*USDA Forest Service, Forest Products Laboratory, Madison, WI, (mdietenberger@fs.fed.us), (cboardman@fs.fed.us)*

Abstract: The urban environment offers significant opportunities to improve sustainability and optimize water resources. Historically, research and software applications have been focused on the built environment (buildings). Cost-effective, practical tools that can assess the impact of different landscape configurations and their interactions with buildings have not been widely deployed. ecoSmart Landscapes (eSL) is a unique SaaS-based platform that helps to bridge this gap. It incorporates modelling and planning tools for the integrated assessment of carbon, water, energy, and fire impacts of landscapes at the residential parcel scale. Analytical and empirical models run concurrently and simulate effects of trees on building energy use, carbon sequestration, rainfall interception and threat posed by burning trees. Effects of shrubs, grass-covered rain gardens, engineered soils and cisterns on surface runoff are simulated as well. eSL's modularity and configurability make it highly customizable and scalable to meet the needs of a wide range of users, from the general public to landscape architects, green industry professionals, and regional planners. The project is a collaborative effort that brings together 1) over 20 years of empirical urban forestry and urban-wildland interface fire research, 2) empirically tested residential scale hydrologic models, and 3) software developed by EcoLayers for integrated, adaptive, and collaborative management of water, land, and environment.

Keywords: ecosystem services; low impact development; sustainability; urban forestry.

1 INTRODUCTION

Urban and suburban environments are a primary source of water consumption, stormwater pollution, energy demand, and GHG emissions. Over the last few decades considerable effort has gone into improving the sustainability of buildings, resulting in a broad range of tools and analytics for assessing the environmental and related economic impacts of architectural design, materials selection, systems sensing and control, and occupant behavior. As the marginal returns on these efforts diminish, urban "green infrastructure" (GI) strategies such as tree planting, rain gardens, and water harvesting will present a significant opportunity to further improve urban sustainability. However, the large scale adoption of these GI strategies will fail unless users can forecast and assess GI impacts with the same rigor, confidence, and reliability that they use for making built infrastructure decisions. This paper describes a science-based, user-friendly tool for assessing the functional performance of selected GI applications.

The U.S. Green Building Council (USGBC) has incorporated the evolving metrics of sustainability into its LEED (Leadership in Energy and Environmental Design) Green Building Rating System. In 2008 the Sustainable Sites Initiative (SITES) extended the benchmarking process to landscapes around buildings. The goal of SITES is to reward landscapes that improve and regenerate ecosystem services that existed at a site in its pre-development state.

SITES provides a comprehensive and integrated approach to evaluating landscape sustainability, with criteria that range from site selection to site design, construction, operations, maintenance, and monitoring. However, most of the criteria and indicators are qualitative. Other modeling tools evaluate the performance of individual GI strategies. For example, the National Tree Benefit Calculator uses inputs of location, species, and tree size to calculate the environmental and economic value trees provide on an annual basis (http://www.treebenefits.com/calculator/). General limitations of existing tools are:

- They employ non-analytical, rule-of-thumb or scale-based metrics that rate sustainability in relative terms.
- Analytical tools are often too simplistic and generalized to produce accurate measures for a specific landscape/building configuration over time.

ecoSmart Landscapes (eSL) strives to overcome these limitations and enable large-scale adoption of GI strategies. Our initial focus is on existing and planned landscapes at the residential parcel scale. Currently targeted GI strategies include:

- Trees and their effects on building energy use, carbon storage, rainfall interception/stormwater runoff, and building damage from trees that catch fire
- Cisterns and their effects on stormwater runoff
- Rain gardens and their effects on stormwater runoff
- Landscape irrigation scheduling and its effect on stormwater runoff
- Engineered soils with tree planting and their effects on stormwater runoff

Objectives of the ecoSmart Landscapes suite of tools are:

- Suitable for use by professionals (e.g., cities, water districts, landscape architects) and the public
- Easy to use, allowing users to explore trade-offs between different landscape configurations
- Accessible over the internet with only a browser and a standard computer
- Modular, so new models and analytics can be easily incorporated
- Capable of tracking change and monitoring and reporting performance of implemented strategies

The numerical models used in eSL are based on over 20 years of research conducted by scientists at the USDA Forest Service and the University of California, Davis. These analytical models are integrated into the EcoLayers SaaS platform designed specifically for integrated, adaptive management of water, land, and environmental assets. eSL draws upon this platform’s capabilities to allow users to enter, select, and edit landscape and building features through a Google Map based user interface. A brief description of each numerical model and the SaaS platform follows. More technical information is available on the website at ecoSmartLandscapes.org.

2 NUMERICAL MODELS

2.1 Tree Size and Growth

The USDA Forest Service has conducted intensive research on predominant tree species in 16 US cities, each in a distinct climate zone (McPherson and Peper 2012). After measuring and aging 17,000 trees, growth equations were developed for 171 species. Urban tree growth does not always follow the "norm" because it may be impacted by management actions, such as crown reduction from pruning. Therefore, five models were tested for each parameter (i.e., predicting diameter at breast height [dbh] from tree age and tree height, crown height, crown diameter and leaf area from dbh) at four weights. Models tested included three polynomial models (linear, quadratic, cubic), as well as loglog and exponential. Analysis was conducted using SAS 9.2 MIXED procedure. Because of small sample sizes the second-order Akaike's information criterion (AIC_C) was used rather than AIC to compare and rank the models. To obtain AIC_C values that would be comparable among all of the models, an additional analysis was performed for the loglog and exponential models. The models with the "best" fit as indicated by having the smallest AIC_C were selected. This unique set of tree growth equations is the foundation for modeling the ecosystem services trees will provide as they mature, such as rainfall interception, energy savings, and carbon storage.

2.2 Energy

ecoSmart Landscapes utilizes an energy model that calculates the effect of trees on hourly heating and cooling energy use for a residential building. It includes a detailed description of building physical characteristics that influence heat transfer. The model incorporates tree shade from user-selected species, size and location, as well as hourly meteorological data modified to account for air temperature and wind speed reductions from increasing tree canopy. Results are expressed as annual changes in heating and cooling energy use due to the presence of selected trees.

In this initial implementation several complexities of the model have been "hidden" from the user. For example, a user can select number of stories and the building vintage (i.e., period of construction). Each vintage defaults to a pre-defined set of building parameters. Tree numbers, locations, species names, dimensions, and/or ages are input via a guided menu. Trees are categorized as existing or planned to gauge effects of retaining or removing existing trees and/or adding new trees. The program uses these data to determine tree shading coefficient and dimensions. Generic tree types, such as broadleaf deciduous large, broadleaf evergreen medium or small coniferous are provided to account for unlisted or unknown species. All tree crowns are ellipsoidal in shape. The model simulates energy effects for a maximum of nine trees.

The shading sub-model quantifies hourly irradiance reductions by trees and other obstructions in various locations around a residence. The program calculates the position of the sun at each hour and then simulates the projection of shadows of trees on the building as a function of the crown shape, size, and opacity. To estimate effects of trees on air temperature, wind speed reductions and energy use, the following parameters used as input for building energy use simulations described earlier (McPherson and Simpson 1999). Canopy cover for air temperature determination is the sum of the crown projection area for all trees in the input file. Peak summer air temperatures were assumed to be reduced by 0.1 °C for each percentage increase in canopy cover. Wind speed reductions were based on the change in total tree canopy plus building cover resulting from the addition of trees based on relationships between wind speed and cover (Heisler 1990).

The building energy sub-model incorporates changes in tree shade calculated by the shading sub-model, as well as changes in air temperatures and wind speeds, to calculate annual heating and cooling energy consumption. Hourly heat gains or losses are computed using data on building structure, insulation level, window configuration, and installed heating/cooling equipment based on standard ASHRAE formulations (ASHRAE 1989). The Radiant Time Series Method (RTSM) is used to convert heat gains to cooling loads for better estimation of peak loads. The performance of the ecoSmart Landscapes energy model has been benchmarked against industry reference model results using the procedure in ASHRAE standard 140 (ANSI/ASHRAE 2004). Preliminary testing demonstrates that annual cooling load estimates are within the range of values for the nine set of model results used in the standard.

2.3 Carbon Dioxide

This model uses tree growth equations with species-specific allometric equations to calculate biomass and carbon storage. To calculate biomass and CO_2 stored in each tree, climate zone, species name, and dbh are used with 26 species–specific allometric equations for trees growing in open, urban conditions. Urban-based biomass equations were developed from street and park trees measured in California and

Colorado (Lefsky and McHale 2008, Pillsbury et al. 1998). The rationale for nearly exclusive use of these equations is that trees in open-grown conditions partition carbon differently than closely spaced trees in forest stands because they do not compete as directly with other trees. Volume estimates are converted to green and dry-weight estimates (Markwardt 1930) and divided by 78% to incorporate root biomass (Nowak 1994). Dry-weight biomass is converted to carbon (50%) and these values are converted to CO_2 (Lieth 1975). The marginal CO_2 stored in year *x* is calculated as the difference between amount stored in year *x+1* and the amount stored in year *x*.

Each tree is matched to one of the 20 to 22 species that were intensively studied in each climates zone's reference city. Correctly matching species insures that the appropriate allometric and growth equations are applied to calculate biomass and annual sequestration rates. Default matches in the technical database were developed by matching mature tree height and crown dimensions reported in the literature with predicted dimensions of the measured species. Users may match species not present in the database using taxonomic relationships or a combination of the tree type, life form and mature tree size.

2.4 Water

This water balance model calculates hourly water fluxes (i.e., surface flow, infiltration, evaporation, transpiration, and interception) for individual land cover polygons using local meteorological and precipitation data. Effects of Best Management Practices (BMPs) on surface runoff and landscape water use are calculated for the year or individual storm events. The user can alter irrigation schedule, add cisterns, promote detention storage with grass-covered rain gardens and engineered soils with tree plantings. This model was tested and calibrated with data collected on adjacent control and treatment landscapes in Los Angeles, CA over a period of two years (Xiao et al. 2007).

Hydrological processess modeled for trees and shrubs are rainfall interception and evaporation, which reduce surface runoff (Xiao and McPherson 2011). Tree and shrub input parameters (i.e., dimensions, leaf surface area, foliation period, crown gap fraction, surface water storage capacity) are obtained from the tree database once the user identifies tree species and shrub type. Interception loss is calculated as the sum of evaporation and surface water storage. Tree and shrub outputs show total evaporation and surface water storage.

Hydrological processess modeled for the grass-covered rain garden include those modeled for trees and shrubs, as well as infiltration and runoff. The user selects from four types of soils (e.g., very well drained to very poorly drained), defines rain garden area and depth, and chooses grass height. The governing equation for modeling the hydrological processes is:

$$\frac{dC}{dt} = p + q_{in} + irr - e - f - r \tag{1}$$

where *C* is surface water storage (m), *t* is time (s), *p* is precipitation rate (m s^{-1}), q_{in} is flow-in surface runoff (m s^{-1}) from adjacent land cover patches or BMPs that have specified the rain garden patch as their surface runoff receiver*, irr* is irrigation rate (m s^{-1}), *e* is evaporation rate (m s^{-1}), *f* is the infiltration rate (m s^{-1}), and *r* is surface runoff rate (m s^{-1}). Surface runoff occurs when infiltration exceeds the water storage capacity and tops the rain garden's berm. Interception loss is calculated as the sum of the total evaporation and final water storage on the grassy surface. Outputs for rain gardens include total precipitation, irrigation, evaporation, infiltration, as well as surface water storage and runoff.

Cisterns receive water from the roof and discharge it for irrigation or surface runoff. The user selects roof and cistern parameters (i.e., roof slope and material, cistern catchment area and volume), while precipitation and evaporation data are obtained from the meteorological database. Cistern outputs depict the volume of roof runoff stored and amounts released as surface runoff.

Engineered soils serve as mini-reservoirs for tree plantings. They consist of rock (75% by volume), preferably lava rock because it is lightweight and highly porous, and regular soil (clay loam, 25%). The pore space stores runoff, while the soil captures mineral elements and contaminants. Nutrients, fertilizers, and pesticides are consumed, degraded, and stabilized by physical and biological processes in the system. For the specific polygon where the engineered soil is applied, the user defines its area and depth, as well as the soil type underneath the tree planting. Infiltration, evaporation, and surface runoff are calculated and the volume of water stored in the engineered soil is depicted.

2.5 Fire

The Fire model evaluates fire risk to a structure from nearby trees by calculating the radiant heat transfer to the walls and roof of the structure. It accounts for radiation shadowing and ground reflections, and reports the percentage of each cladding surface that is damaged or ignited. The model assumes all trees are burning simultaneously within a finite amount of time when determining the building surface temperatures. Model inputs include the building geometry and surface material properties, as well as tree locations, height, and foliar biomass.

The radiation heat transfer is calculated from each burning tree crown to each one of hundreds of small areas spread across each building surface. The formulae for flame characteristics of burning trees and the radiative heat transfer to differential surfaces are from the Handbook of Fire Protection Engineering (DiNenno et al. 2008). The heat release rate (HRR) of a typical burning tree is assumed constant for a finite time and calculated based on the foliar biomass (mass) and moisture content (MCper) using equation 2:

$$(2) \qquad HRR = \frac{2 \times mass \times 700}{(1 + 0.1295 \times MCper)}$$

Flame height is calculated from the HRR and tree diameter (TreeD) using equation 3:

$$(3) \qquad FlameH = -1.02 \times TreeD + 0.235 \times HRR^{0.4}$$

The burn time of a tree is equal to the foliar mass times the foliar heat of combustion divided by the HRR of the tree. In this worst case analysis all trees are considered to be at the same low moisture content and burning at the same time from effective firebrand spotting. This condition results in similar burn times from all tree fires. The radiant heat transfer calculation assumes the flame of the burning leaves is a cylinder, homogeneous and its radiant properties are those of smoke for burning wood. Under these conditions heat transfer from the source is blackbody emissive power as reduced by flame emissivity and view factors calculated for small areas on a building surface.

Because the burning time of a tree is much shorter than that of a typical structure fire, the imposed radiant heat flux from tree fires as calculated with a transient heat conduction model can be considerably greater than the critical heat flux before a building surface ignites. In general, this would allow the trees to be much closer to a structure than the distance required between structures themselves. Wall and roof material properties, along with damage and ignition temperatures, ground reflectivity, and tree dimensions and properties are provided in tables. The fire risk is mitigated by the appropriate selection of tree sizes and locations, and appropriate cladding surface materials that reduce the percentage of each surface that is reported as damaged or ignited.

3 ECOLAYERS PLATFORM

eSL is hosted on the EcoLayers software platform, designed specifically for integrated, collaborative, and adaptive management of water, land, and environment over different geographic scales. In eSL, this geographic scale is the residential parcel, which can be extended to include university and commercial campuses for several of the GI components.

An architectural overview of the EcoLayers platform is shown in Figure 1. A Google Maps based user interface is shared among all GI components. To start entering data, the map first zooms to the user's address entered during registration and then guides the user to sequentially enter data for the parcel, building, roof, trees, cistern, turf areas, shrub areas, and engineered soils areas. Tools allow the user to delineate or mark each GI feature on the property as viewed on Google Maps.

Users can run individual numerical models or any combination of the models. The various eSL models are scheduled to run as services within the EcoLayers software environment. Changes to each user's landscape profile are also detected automatically and the appropriate models are executed for the new input.

Users can assign *Existing* or *Planned* status to all GI features except the building. Model runs are performed for the current year or forecasted through the estimated life of each tree. Numerous outputs in the form of tables and charts show the individual and cumulative impacts of each GI feature. The fire damage potential is shown by appropriately color coding the building walls. eSL was initially rolled out for California, but national application is possible depending on market interest.

The technology platform consists of Windows servers, Microsoft SQL 2008, Google Maps, and various third party components. Hardware consists of two quad core processors each with 24 GB of RAM. The energy models are the most computationally intensive, taking up to a few minutes to run concurrently for multiple users. The technical GI database can be separated from the EcoLayers framework and user database, allowing for a distributed SaaS implementation on different servers for different customers.

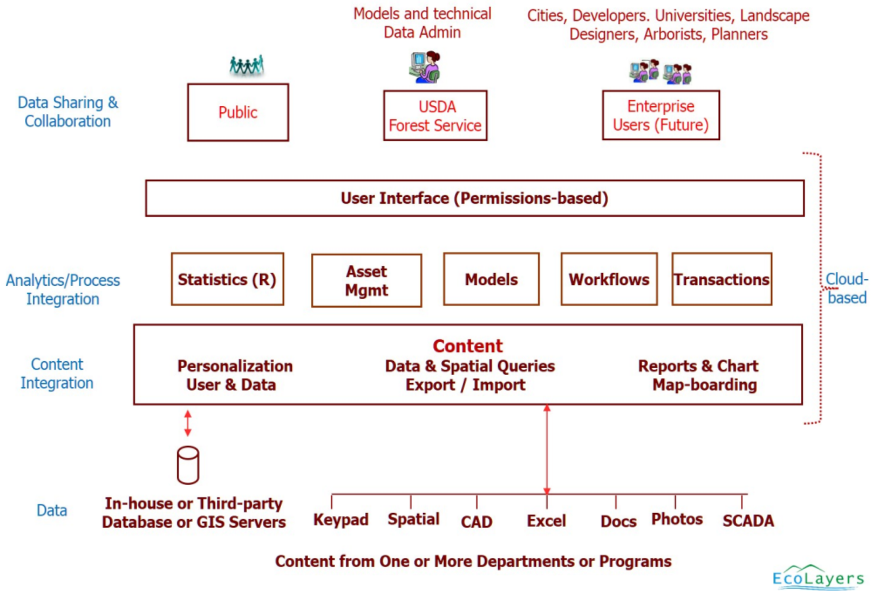

Figure 1. Architectural overview of the EcoLayers platform.

4 FROM SUSTAINABLE LANDSCAPES TO SUSTAINABLE CITIES

Landscapes and trees typically represent the largest "green" asset in urban and suburban environments. eSL allows the scaling-up of GI benefits from individual parcels to neighborhood, city, and regional scales. Application of innovative sustainable strategies can benefit from significant economies of scale. Examples include:

- Defer or avoid new investments in stormwater management infrastructure, especially in regions with aging combined sewer and sanitation systems
- Energy conservation programs that can substantially reduce peak and base energy demand

- Assess fire risks for a community
- Optimize local water resources through rain water harvesting at neighborhood scale
- Prioritize resources for water conservation programs.

Although eSL quantifies environmental impacts of several GI strategies, its full potential has not been realized. Green roofs are not included at this time. Assigning a monetary value to environmental impacts is left to the user, as these can be very site and regionally specific. We assume that for certain impacts, such as stormwater retained and energy saved, results are cumulative when scaled over multiple parcels.

The extent to which eSL's numerical models have been field tested varies by model. Carbon storage estimates are based on the most current tree growth and biomass equations available. The water model was calibrated with measurements recorded over several years at test sites in Los Angeles (Xiao and McPherson 2011). The performance of the ecoSmart Landscapes energy model has been benchmarked against industry reference model results using the procedure in ASHRAE standard 140 (ANSI/ASHRAE 2004). Preliminary testing demonstrates that cooling load estimates are within acceptable tolerance limits. The fire model is based on several simplified assumptions related to combustion rates and requires further empirical testing. Research is underway to more fully calibrate and verify the accuracy of eSL's numerical models where needed.

5 CONCLUSIONS

A practical tool is now available for evaluating GI applications at the residential parcel scale. With ecoSmart Landscapes, sustainability impacts can be assessed quantitaitvely for a variety of GI strategies. eSL is a unique tool for assessing GI impacts because it combines spatial delineation of individual GI elements with scientifically sound modeling techniques. Besides serving as a tool for planning and design of sustainable landscapes, with a few modifications eSL can also be used for education and training on GI applications in academic and professional settings.

6 REFERENCES

ANSI/ASHRAE (2004) *Standard 140-2004, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs,* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE (1989) *1989 ASHRAE Handbook of Fundamentals,* Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers.

DiNenno, P. J., Drysdale, D., Beyler, C. L., Walton, W. D., Custer, R. L. P., Hall, J. R. and Watts, J. M. (2008) *Handbook of Fire Protection Engineering,* 4th Edition ed*.,* Bethesda, MD: Society of Fire Protection Engineers.

Heisler, G. M. (1990) Mean wind speed below building height in residential neighborhoods with different tree densities, *ASHRAE Transactions,* 96, No.1, 1389-1395.

Lefsky, M. and McHale, M. (2008) Volume estimates of trees with complex architecture from terrestrial laser scanning, *Journal of Applied Remote Sensing* 2, (1):023521-023521-19.

Lieth, H. (1975) Modeling the Primary Productivity of the World. in *Primary Productivity of the Biosphere*, New York: Springer-Verlag New York Inc., 237-263.

Markwardt, L. J. (1930) *Comparative Strength Properties of Woods Grown in the United States*, Washington, DC: U.S. Department of Agriculture Forest Service.

McPherson, E. G. and Peper, P. J. (2012) Urban tree growth modeling, *Arboriculture & Urban Forestry* 38(5), 175-183.

McPherson, E. G. and Simpson, J. R. (1999) *Carbon Dioxide Reductions Through Urban Forestry: Guidelines,* Albany, CA: USDA Forest Service, Pacific Southwest Research Station.

Nowak, D. J. (1994) Atmospheric carbon dioxide reduction by Chicago's urban forest in McPherson, E. G., Nowak, D. J. and Rowntree, R. A., eds., *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*, Radnor, PA: USDA Forest Service, Northeastern Forest Experiment Station, 83-94.

Pillsbury, N., Reimer, J. L. and Thompson, R. (1998) *Tree Volume Equations for Fifteen Urban Species in California*, San Luis Obispo, CA: Urban Forest Ecosystems Institute, California Polytechnic State University.

Xiao, Q. and McPherson, E. G. (2011) Rainfall interception of three trees in Oakland, California, *Urban Ecosystems,* 14, 755-769.

Xiao, Q., McPherson, E. G., Simpson, J. R. and Ustin, S. L. (2007) Hydrologic processes at the urban residential scale, *Hydrological processes,* 21, 2174-2188.