i-Tree Tools Assist with Strategically Designing Tree Cover and Improving Community Resilience

by Theodore A. Endreny

Ecological Engineering as a Design Approach to Improve Sustainability

Ecological engineering involves the intentional design with nature to convert pollution into resources such as fiber, fuel, food, and a nurturing climate for the well-being of biodiversity and humans *(Endreny, Santagata et al. 2017)*. Human creation of a new geologic epoch, the Anthropocene, attests to the disfigurement of global air, land and water resources through designs uncoupled from nature *(IPCC 2022)*. Planet Earth in the Anthropocene unleashes natural disasters with increasing ferocity, is no match to human-created pollutants (e.g., carcinogenic forever chemicals), and has awakened our humility to ask how can we restore balance *(Nelson, Bledsoe et al. 2020)*.

Balance will involve addressing environmental injustices characterized by an unequal distribution of pollution and disaster, with the most vulnerable communities taking the brunt of impact *(Hoffman, Shandas et al. 2020)*. This is our challenge: to improve the world by chasing down sustainability, defined to include environmental, social and economic justice.

The aim of this article is to explain how i-Tree tools can help us design sustainable communities with strategic use of tree cover and related nature-based systems.

Supported i-Tree Tools and Utilities for Use in Tree-based Designs

The i-Tree tools and supporting utilities are freeware *(www.itreetools.org)* developed through a peer-reviewed process with the goal of assisting individuals and communities obtain ecosystem services and benefits based on the science of trees.

The benefits of trees accrue largely from the system of ecosystem services occurring during photosynthesis. Ecosystem services have been placed into four broad categories:

1) provisioning (e.g., food, fiber, fuel, water)
2) regulating (e.g., climate, flood, pollution and disease control)
3) supporting (e.g., pollination, soil formation, nutrient cycling)
4) cultural (e.g., spiritual and recreational, noting that just seeing green improves health [Millennium Ecosystem Assessment 2005])

While the i-Tree tools can estimate benefits totaling billions of dollars annually for some regions *(Endreny, Santagata et al. 2017)*, these monetary benefits are typically limited to air pollutant removal (carbon monoxide, nitrogen dioxide, ozone, particulate matter, sulfur trioxide), stormwater runoff avoided, building energy savings, and carbon dioxide sequestration and avoided emissions; hence, these tools are known to underestimate by not including many services. The underestimation is not intentional, but instead society has not yet quantified values for many beneficial services trees contribute to human well-being. Uncounted ecosystem services of disease prevention and recovery, school and student performance, and happiness are connected to society's greatest expenses of health care, education and defense (*Endreny 2018*).

i-Tree Landscape Tool

The i-Tree Landscape tool is a good place to start for landscape designs, as it provides a rapid assessment of existing, aka base-case, tree cover using classified aerial and satellite imagery, and then recommends priority planting to maximize benefits and reduce pollution. The user defines objectives and constraints to guide the prioritization, such as addressing:

a) racial, economic or other inequities as categorized by the U.S. census data
b) health risk such as pollution exposure threats
c) forest risk such as pests
d) present and future climate threats
e) much more, including plantable space

i-Tree Landscape develops its prioritization by cross-comparing two or more polygon analysis areas, which include census block groups, places (e.g., towns), congressional districts, and watersheds organized by 12-digit hydrologic unit codes (HUC) and river basins. i-Tree Landscape reports the benefits of tree cover in scientific units (e.g., mass of greenhouse gas sequestered or volume of stormwater avoided) and in monetary units based on established prices for carbon, water, energy and health care markets.

i-Tree Species Utility Tool

The i-Tree Species utility tool guides users in selecting the optimal tree species for a planting, based on taking inputs of location (e.g., suitable hardiness zone), height constraints (e.g., avoid utilities), and preferences for many functions, which include services and disservices. The selectable functions within i-Tree Species include air pollutant removal, lowering the disservice of volatile organic compound emissions (which can be reduced given they vary by species), carbon storage, wind reduction, air temperature reduction, UV radiation reduction, building energy reduction, streamflow reduction and low allergenicity. In locations with suitable deciduous and evergreen trees, the evergreen trees, which photosynthesize all year, will generate more benefits. If a species of interest is not present within this utility tool, there is the i-Tree Database utility tool for recommending new species to include. Similarly, if the region of interest is not present then users can use this utility tool to update the location database with weather and pollution data.

i-Tree MyTree Tool

The i-Tree MyTree tool is a good place to start improving the world for property designs, with the tool's focus on analyzing a specific tree or group of trees at one address. The i-Tree MyTree tool retrieves information on tree location, species (accepting common names), condition (e.g., crown health), size, sun exposure and distance from a building, identifying the tree as a new planting, removal, replacement, a special class such as heritage, memorial or specimen, or whether it is part of a larger planting. In an effort to make model output easy to digest, the benefits are presented in a format similar to nutritional labels on food packaging, reporting scientific and monetary values.

i-Tree Eco Tool

The i-Tree Eco tool is for projects involving field collected data for individual trees, noting their location, species, structure (e.g., diameter a breast height [DBH], canopy volume), condition

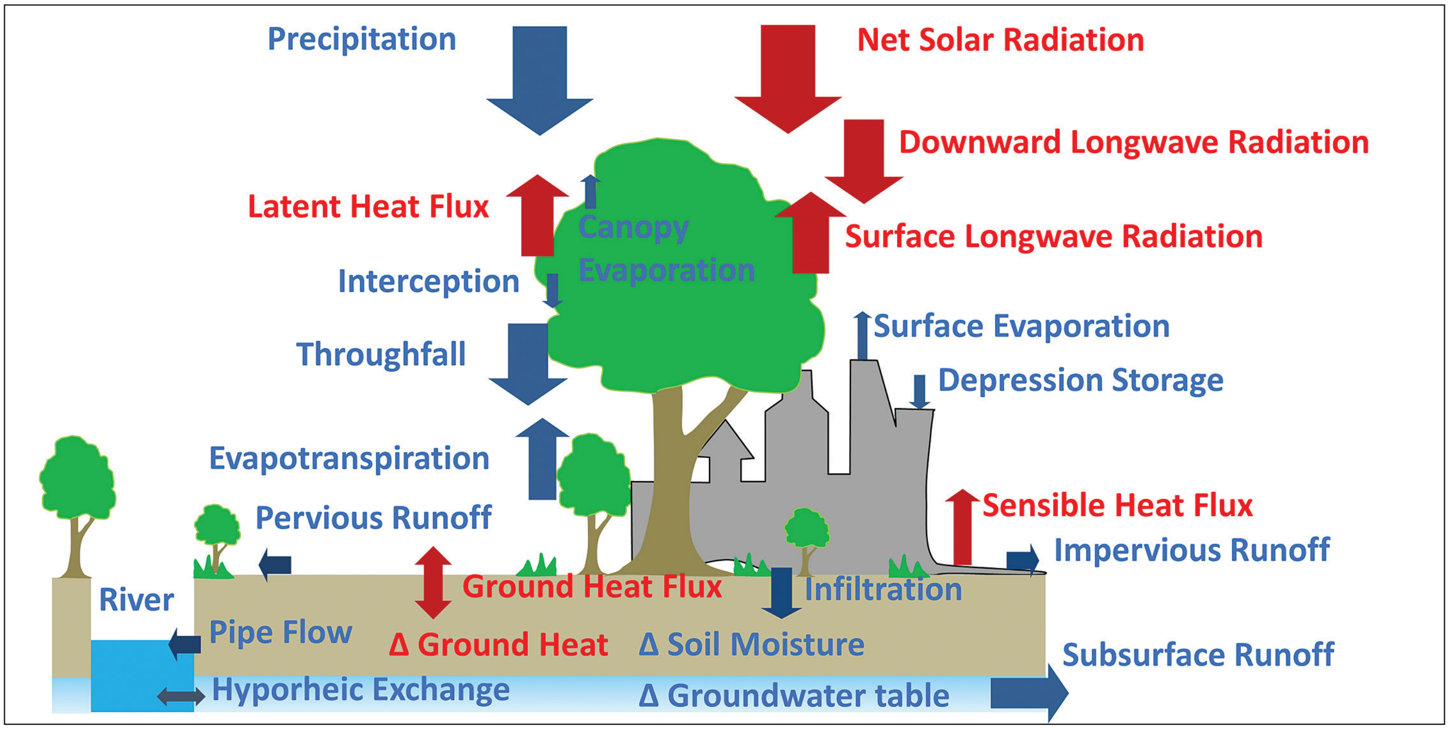

Figure 1. Conceptual model of i-Tree HydroPlus tool, showing its simulated fluxes and storages of water and energy overlaid on a cross section of Earth's critical zone. By solving the equations in this model, the tool can determine tree planting strategies. *Image by T. Endreny*

(e.g., dieback, pruning), ground cover, tree pests, recommended management (e.g., correcting sidewalk or utility interference), and more. i-Tree Eco data are collected using either a complete inventory (e.g., every tree with a DBH greater than 1 inch), or from random plot samples, which include the option to include understory shrub inventories relevant to bird habitat. The i-Tree Eco tool contains the Forecast model, which can simulate new plantings and mortality rates based on tree condition, as well as due to pest outbreaks and severe weather (e.g., hurricanes and ice storms). The monetary benefits from trees reported by i-Tree Eco simulations are as accurate as the data collection.

i-Tree Design and Planting Tools

The i-Tree Design and Planting tools simulate tree benefits, including tree-building interactions, at a spatial scale overlapping or exceeding the i-Tree MyTree tool, but do not extend out to i-Tree Landscape scale. The i-Tree Design and Planting tools will simulate new tree plantings, removal and replacement. The i-Tree Design and Planting tools begin by collecting location data, handling areas with multiple buildings, such as a neighborhood block or school campus. Tree species, size, light exposure and condition are then selected by users.

The i-Tree Design tool enables users to place these trees as icons within a color-coded map of optimal planting polygons about a building. The i-Tree Planting tool replaces the map with a spreadsheet, asking users to enter the compass bearing and distance from tree to building. Tree distance and direction from a building affect heating and cooling costs; in New York, planting within 20 feet of the southwest side of the building typically brings additional winter heating costs, even for deciduous trees due to the shadow cast by their limbs.

The benefits predicted by i-Tree Design and Planting are reported in scientific and monetary units for each and any year, as well as for any duration between 2 and 99 years. To the delight of those wishing to see the future, the i-Tree Design tool graphically presents tree crown growth on the map, revealing interaction with other plantings and the building, which some may consider priceless information.

i-Tree Canopy Tool

The i-Tree Canopy tool is for collecting the highest accuracy data on land cover via photointerpretation in Google Maps and requires the most work of the above tools. The i-Tree Canopy tool allows the user to draw a sampling polygon about the area of interest or select from the same polygons used in i-Tree Landscape. Depending on perspective, the work or pleasure then begins, with the user classifying the land cover at a randomly placed crosshair, repeating this process hundreds of times, ending when the standard error of the estimate is deemed acceptable, e.g., less than 2%. Obtaining a final value for spatial extent of tree cover then allows the i-Tree Canopy tool to sample its database and estimate the scientific and monetary value of ecosystem services.

Research Suite i-Tree Tools and Utilities for Use in Nature-based Designs

The i-Tree tools can assist with restoration designs beyond tree plantings, such as installation of green infrastructure, mitigation of urban heat islands, rewilding of rivers, and treatment of nonpoint source runoff. These tools are within the i-Tree Research Suite, which is freeware designed with peer-reviewed theory to inform nature-based design, like those tools described earlier, but without technical support from the i-Tree consortium.

The i-Tree HydroPlus tools of i-Tree Hydro, i-Tree Cool Air, i-Tree Cool River and i-Tree Buffer generally require greater effort to obtain inputs, run simulations, and translate scientific values into monetary benefits. These tools share a common starting point in modeling the hydrologic cycle and its interactions with energy and biogeochemical cycles ***(Figure 1)***. Managing water resources to provide drinking water, sanitation, hygiene, food, and energy

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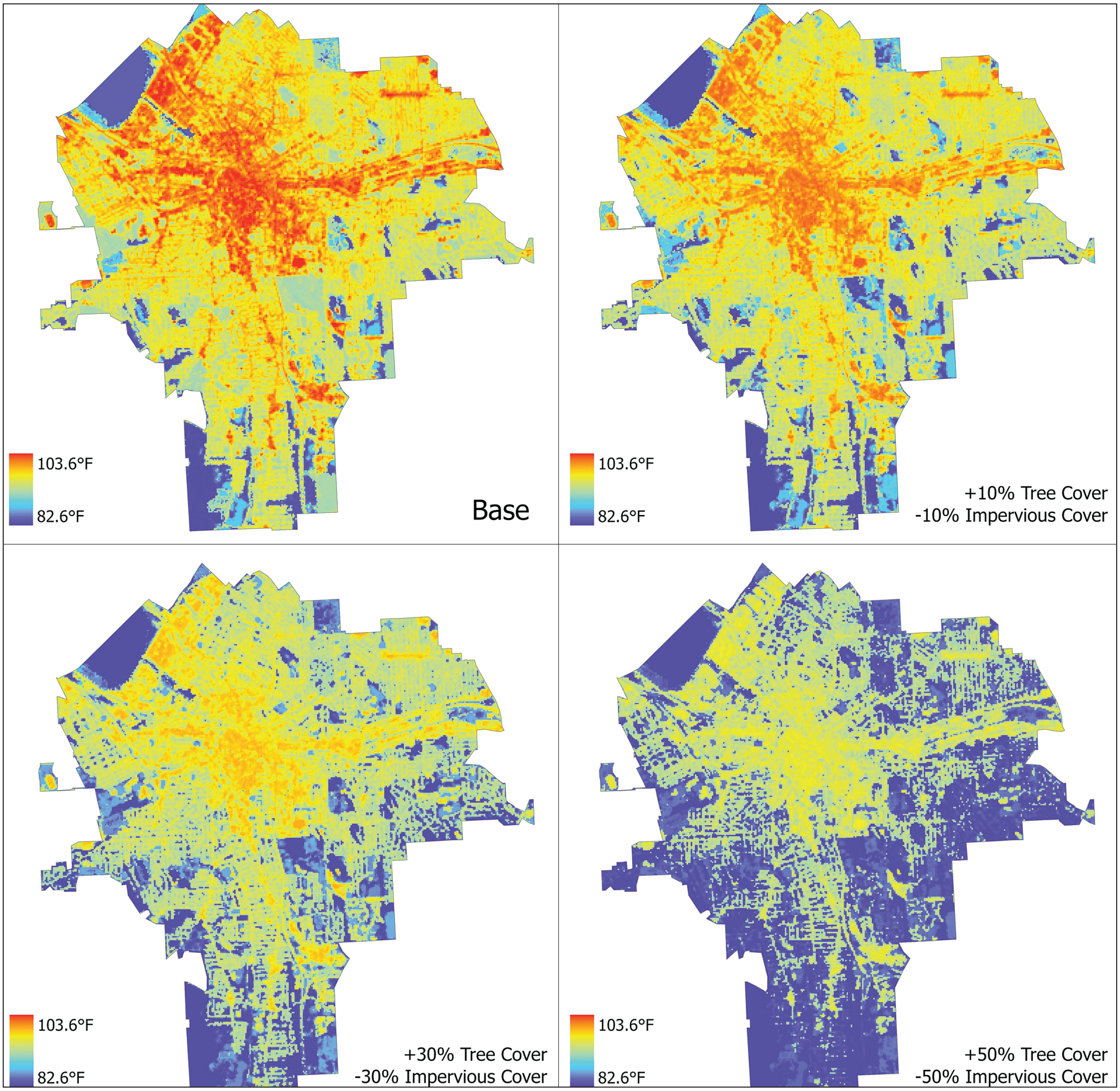

Figure 2 Heatwave maps of air temperature created by the i-Tree Cool Air model for Syracuse, New York, at 3 p.m. July 9, 2020, when the weather station recorded 95° F. The upper left map is for actual land cover, and proceeding clockwise the maps show potential cooling through increased tree cover and decreased impervious cover, starting at 10% changes and extending to 50% changes. *Image by T. Endreny*

allows communities to take the next steps in sustainable development of reducing poverty, increasing peace and prosperity, and improving biodiversity *(WWAP 2018)*.

In the past few decades, the management of stormwater runoff systems has undergone major changes, shifting from limited-focus plans (e.g., flood control) to approaches with multiple objectives to keep water on-site and deliver improved environmental, economic, social and cultural outcomes *(Fletcher, Shuster et al. 2015)*. Runoff is kept on-site using green infrastructure, or equivalent measures such as sustainable drainage systems, low-impact development and best management practices. These devices have the common feature of receiving runoff from upslope contributing areas or direct rainfall to satisfy other needs, including a chance for the water to infiltrate into native soils and replenish groundwater systems. One reason for the limited adoption of green infrastructure, both rural and urban installations, is the need for design plans that address local site concerns and operate effectively at a range of scales *(WWAP 2018)*. Hence the development of the i-Tree Research Suite.

i-Tree Hydro Model

The i-Tree Hydro model simulates the water and pollutant balance for watersheds or smaller parcels using base-case and alternative scenarios, such as with changes to tree cover or the installation of green infrastructure. The i-Tree Hydro green infrastructure options include bioretention cells, swales, rain gardens, infiltration trenches, porous pavement, green roofs, rain barrels, and rooftops disconnected from storm sewers; most options can also interact with groundwater and be used to remove pollutants.

The model is run from a command line interface, with inputs organized via an XML configuration file. The required inputs include weather or storm data, elevations, land cover and soils data. Land cover data often come from the i-Tree Canopy tool. Weather station data are typically collected at a one-hour time step, but the model accepts finer resolution data, while design storm data, such as intensity-duration-frequency rainfall, improves analysis of small parcels during intense events. Elevation maps are needed to create a topographic index of wetness likelihood for moving groundwater laterally, and land cover and soils data are required for determining canopy interception, surface ponding, infiltration, pollutant loads, and the interaction with weather for estimates of evapotranspiration. The model comes with reference pollutant concentration values (biological oxygen demand, chemical oxygen demand, copper, phosphate, nitrate, lead, total Kjeldahl nitrogen, total phosphorus, total suspended solids, zinc) provided by federal agencies.

The model offers simulations that are deterministic, spatially lumped or distributed, single event or continuous, and can run a one-year analysis in seconds. The i-Tree Hydro output options include hydrographs, pollutographs, summary mass balances of water budgets (e.g., depth of water intercepted or evapotranspired by the tree canopy) and pollutant loads, and detailed performance data on any green infrastructure device with respect to water stored in its vertical layers, runoff avoided, and pollutants removed.

i-Tree Cool Air Model

The i-Tree Cool Air model simulates the urban heat island phenomenon ***(Figure 2)***, which is characterized by disproportionately warmer nighttime and daytime air temperatures over developed versus natural land surfaces. This warming is due to how radiation is partitioned between latent and sensible heat (e.g., trees transpire water and use radiation that would otherwise warm the air), as well as differences in heat transfer properties and anthropgenic sources of heat.

The i-Tree Cool Air model simulates watersheds or smaller parcels using base-case land cover and alternative scenarios, such as increased tree cover and water availability. The required inputs include weather station data, typically at a one-hour time step, maps of census block groups, elevation, tree cover, impervious cover and land cover classes (e.g., Class 21 is developed open space), as well as soil and surface parameters regulating the water and energy cycle. The model comes with reference heat transfer parameters for most National Land Cover Data classes, with parameters representing the urban canyon effect on amplifying longwave radiation.

The i-Tree Cool Air map pixel size determines the spatial resolution of the model simulation, with 10 to 300-meter resolutions proven to work well. The simulations are deterministic, spatially distributed, single event or continuous, and can run a one-day analysis in minutes to tens of minutes depending on city size and pixel resolution. The i-Tree Cool Air output options include air temperature maps, time series and statistics including maximum temperatures, heat indices and wind chill, along with water and energy balances. The model uses the census block group maps, or equivalent maps, to statistically organize some outputs by neighborhoods.

i-Tree Cool River Model

The i-Tree Cool River model simulates the temperature of surface waters, which is often a limiting condition to supporting fishing, drinking and swimming standards for waterways. The water temperature is simulated as a function of riparian shade, upstream inflows, lateral inflows including from warm reservoirs or stormwater discharges, groundwater inflows including from green infrastructure recharge, hyporheic flux (e.g., mixing of surface and subsurface water), and the radiation from sky and land surfaces. The required inputs include weather station data, upstream river discharge and water temperature, discharge and temperature for any lateral inflow, channel geometry and substrate data for each cross-section, and associated riparian geometry or its effect on water surface shade.

The model uses one-dimensional simulation to model single reaches or longer river channels using base-case and alternative scenario configurations of river geometry and riparian conditions. The river geometry can represent restoration of pools and riffles, which will induce hyporheic exchange and contribute to thermal refugia and more suitable habitat, and a dynamic boundary can be used to determine the restoration length needed to achieve target temperatures. The simulations are deterministic, spatially distributed between cross-sections, single event or continuous (e.g., dynamic storm events), and can run a one-day analysis in seconds to tens of minutes depending on river length and cross-section resolution. The i-Tree Cool River output options include water temperature data as a function of river distance or time, as well as energy balance data on how incoming radiation partitioned between latent and sensible heat.

i-Tree Buffer Model

The i-Tree Buffer model simulates the spatial distribution of phosphorus and nitrogen runoff across the landscape to identify nonpoint source pollution hot spots and nutrient loading to receiving waters, assisting with total maximum daily load regulations. The nonpoint source runoff is simulated as a function of edge-of-field nutrient loads available for runoff to receiving waters, the runoff likelihood of each map location, and the interaction of runoff flow paths with nutrient filtering via wetland trapping and vegetation uptake. The required inputs include maps of elevation, tree cover, impervious cover, land cover, soil cover and river networks; for stochastic estimates of nutrient loads, a decade or more of daily average discharge data are used to generate probabilities.

The i-Tree Buffer model comes with reference edge-of-field nutrient loads, in the form of export coefficients, that are selected based on National Land Cover Data class and watershed 8-digit HUC. The model offers simulations that are deterministic or stochastic, spatially lumped or distributed, single event or continuous, and can run one year or longer analyses in seconds. The i-Tree Buffer output options include maps of nutrient hot spots, maps of vegetative buffers, and data tables of loads to receiving waters.

Putting Ideas into Action to Improve the World

Restoration opportunities are available globally, including rural areas, where strategic designs with nature can deliver ecosystem services and improve human health and well-being. Currently, the trend is declining tree cover due to climatic disruption forces and anthropogenic forces, including the woeful act of intentional tree removal to expedite designs without nature in mind. The time to

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act is now, by protecting existing resources and establishing new plantings that need time to mature to increase their own resilience and that of surrounding communities. Tree cover and associated ecosystems improve biological diversity, climate change adaptation, climate change mitigation and pollutant removal. Risks to human health and well-being are increased by climate change, which brings unprecedented interactions of heat waves, infectious disease, and pollution to a population that is growing with respect to head count, inequities and vulnerability. The i-Tree tools are available to help those responding to these challenges with nature-based solutions.

Theodore A. Endreny, Ph.D., PE, PH, is a professor at the State University of New York College of Environmental Science and Forestry and may be reached at te@esf.edu.

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In urban communities, tree cover and related nature-based systems provide benefits that include air pollutant removal, temperature regulation and disease prevention, contributing to overall human well-being.

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