



Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Northern Research Station | General Technical Report NRS-200-2023 | April 2024

Understanding i-Tree: 2023 Summary of Programs and Methods

David J. Nowak



i-Tree™

Citation

Nowak, David J. 2024. **Understanding i-Tree: 2023 summary of programs and methods.** General Technical Report NRS-200-2023. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 103 p. [plus 14 appendixes]. <https://doi.org/10.2737/NRS-GTR-200-2023>.

Abstract

i-Tree is a suite of computer software tools developed through a collaborative public-private partnership. These tools are designed to assess and value the urban forest resource, understand forest risk, and develop sustainable forest management plans to improve environmental quality and human health. This report provides details about the underlying methods and calculations of these tools, as well their potential limitations. Also discussed are the history of i-Tree, its future goals, and opportunities to facilitate new science and international collaboration.

This report is a revision to ones previously published in 2020 and 2021. It reflects updates to procedures and values.

Keywords: air pollution removal, carbon sequestration, computer modeling, economic valuation, ecosystem services, forest inventory, forest risk, urban forestry

The Author

DAVID J. NOWAK is an emeritus senior scientist with the USDA Forest Service's Northern Research Station at Syracuse, New York.

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

Manuscript received for publication August 2023

Published by
USDA FOREST SERVICE
ONE GIFFORD PINCHOT DRIVE
MADISON, WI 53726
April 2024

Visit our homepage at <https://www.fs.usda.gov/research/nrs>

Understanding i-Tree: 2023 Summary of Programs and Methods

David J. Nowak

PREFACE

Overview of Changes to this Document

Collaborators continue to update and expand i-Tree suite of computer software tools. This document, “Understanding i-Tree: 2023 Summary of Programs and Methods,” provides updates from the previous (2021) and original (2020) version.

Revisions in the main document include:

- Text and many figures have been updated to reflect most recently available data.
- The list of insects and diseases evaluated has expanded.
- In many cases, previous descriptions of “Planned Improvements” have been eliminated as these are now incorporated in i-Tree tools. In other cases, new “Planned Improvements” have been added.
- Additional Ecosystem Services in i-Tree Eco have been incorporated: Allergenicity Index, Leaf Nutrients, and Wood Products.
- “OURTREES” has been added to the list of i-Tree Tools.
- Hyperlinks and URLs have been updated, to the extent possible.

In addition:

- Several countries and regions have been added to the information in appendix 9, including areas in South America, the Caribbean, and Asia.
- Biomass equations have been updated in appendix 10.
- In appendix 11, the list of genera and species for which wood density values are presented has greatly expanded.

For updated information on i-Tree, go to the change logs at:

https://www.itreetools.org/documents/739/ScienceUpdates_92021.pdf and
<https://www.itreetools.org/tools/i-tree-version-updates>.

CONTENTS

Executive Summary.....	1
Introduction	2
What is i-Tree?.....	2
Vision.....	2
Goals.....	2
Tools.....	3
Core Programs.....	4
Utilities	6
Partner Tools Powered by i-Tree.....	7
Research Programs	7
Legacy Programs	7
Partnerships.....	8
History.....	9
i-Tree Timeline	9
i-Tree 2023	12
i-Tree and Urban FIA	14
Future Goals	16
Methods, Advantages, and Limitations.....	19
Assessing Forest Structure in i-Tree Eco.....	20
Tree Measurements	21
Leaf Area and Leaf Area Index.....	22
Leaf Biomass.....	24
Tree Biomass	24
Uncertainty in Tree and Leaf Estimates	25
Plot Measurements.....	26
Sample Totals and Errors	27
Assessing Structural Metrics and Risks in i-Tree Eco	27
Tree Species Diversity and Range.....	27
Potential Insect and Disease Effects.....	30
Invasive Species	32
Structural Valuation.....	32
Assessing Ecosystem Services and Values in i-Tree Eco	35
Air Pollution Removal	35
Allergenicity Index.....	39
Building Energy Use and Emissions.....	40
Carbon Storage and Sequestration	43
Food Provisioning Services.....	46
Leaf Nutrients	46
Oxygen Production	47
Stream Flow and Water Quality.....	47

Volatile Organic Compound Emissions	49
Ultraviolet Radiation	51
Wood Products.....	52
Wildlife Habitat.....	52
Summary of Uncertainty and Economic Valuation.....	53
Other i-Tree Tools	56
i-Tree Canopy	56
i-Tree Cool River	57
i-Tree County.....	57
i-Tree Design	58
i-Tree Forecast.....	58
i-Tree Harvest	61
i-Tree Hydro	61
i-Tree Landscape	63
MyTree.....	74
OurTrees.....	74
i-Tree Planting.....	75
i-Tree Projects.....	75
i-Tree Species	75
i-Tree Streets.....	76
i-Tree Wood Marketplace.....	77
Acknowledgments.....	78
Literature Cited	79
Appendix 1: i-Tree Staff and Collaborators.....	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix1
Appendix 2: i-Tree Links	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix2
Appendix 3: Shading Coefficients	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix3
Appendix 4: Conversion Factors for Leaf Area to Biomass	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix4
Appendix 5: Conversion Factors for Shrub Volume to Biomass	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix5
Appendix 6: Invasive Plant Species.....	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix6
Appendix 7: Compensatory Value of Trees	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix7
Appendix 8: Average Energy Costs.....	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix8
Appendix 9: Energy Conservation Estimates for Buildings in non-U.S. Countries	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix9
Appendix 10: New Biomass Equations.....	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix10
Appendix 11: Wood Density Values	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix11
Appendix 12: Volatile Organic Compounds (VOC) Emission Rates.....	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix12
Appendix 13: Equations for Tree Height, Crown Height, and Crown Width.....	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix13
Appendix 14: Partial List of Publications Referencing i-Tree Tools	https://doi.org/10.2737/NRS-GTR-200-2023-Appendix14

EXECUTIVE SUMMARY

i-Tree is a suite of computer software tools developed through a collaborative public-private partnership. These tools are designed to engage urban and rural populations in assessing and valuing their forest resource, understanding forest risk, and developing sustainable forest management plans to improve environmental quality and human health. The tools can assess individual trees and forests in both urban and rural areas. i-Tree's vision is to improve forest and human health through freely available, user-friendly technology that engages people throughout the world in enhancing forest management and resiliency. While the science and models at the core of i-Tree have been in development since the mid-1990s, the i-Tree program suite was first released in 2006 as a framework for science delivery.

i-Tree programs engage citizens, youth, and land managers in understanding their local forest resource, its value, and risks to sustaining forest health. The tools aid in forest management decisions to improve forest and human health and well-being. Though originally developed as tools to aid in urban forest management, the i-Tree suite is being used in rural forests and is being integrated within the USDA Forest Service's Forest Inventory and Analysis program.

Over the past decade, the i-Tree suite's usage and capabilities have increased tremendously. As of the end of 2023, there have been more than 910,000 users of i-Tree tools in 185 countries. A nonexhaustive literature search revealed over 1,000 articles that either use i-Tree, developed methods for i-Tree, or make reference to i-Tree or precursor programs (i.e., UFORE and STRATUM) ([appendix 14](#)).

The goal of this document is to improve the understanding of i-Tree by summarizing i-Tree's:

- ✿ History and future goals
- ✿ Program methods and potential limitations
- ✿ Opportunities to facilitate new science and international collaboration

INTRODUCTION

i-Tree is a suite of computer software tools developed through a collaborative public-private partnership. The tools are freely available from i-Tree website (www.itreetools.org) and are designed to be accessible and user-friendly and to aid urban and rural land managers and the general public in:

- ✿ Assessing and monitoring their local forest resource
- ✿ Understanding the services and values provided by trees and forests
- ✿ Evaluating risk to forest and human populations
- ✿ Developing sustainable forest management plans
- ✿ Improving environmental quality and human health
- ✿ Selecting appropriate tree species and locations
- ✿ Engaging stakeholders and public audiences

While development started in the mid-1990s, the i-Tree suite was first released in 2006. Over the years the i-Tree suite has grown, adding new tools, methods, and publications. Due to i-Tree's growth in use and capabilities, this document is designed to help readers understand:

- ✿ What is i-Tree?
- ✿ Where is i-Tree headed?
- ✿ What are the current methods and limitations related to calculating ecosystem services and values?

Through a better understanding of i-Tree, international collaboration can be enhanced to help improve these tools for forest managers across the globe.

WHAT IS I-TREE?

i-Tree is a suite of computer programs designed to estimate forest structure, ecosystem services, values, and risks related to forests and people. It was originally developed in the 1990s as the Urban Forest Effects model (UFORE), with a street tree assessment tool (STRATUM) added in the early 2000s. Today i-Tree includes a variety of tools that are used globally and encompass trees on all urban and rural lands.

Vision

To improve forest and human health through user-friendly technology that engages people around the world in enhancing forest management and resiliency.

Goals

To attain this vision, i-Tree continues to develop tools with the ultimate goals of allowing anyone to:

- ✿ Assess local forest conditions

- ✿ Quantify multiple ecosystem services and values derived from forests
- ✿ Determine local risks to forest and human health
- ✿ Calculate how changes in forest structure will lead to changes and tradeoffs among ecosystem services and values
- ✿ Develop best forest management strategies to enhance desired ecosystem services and forest and human health
- ✿ Determine the best tree species, locations, and planting rates to optimize ecosystem services and values through time and across space to enhance human health and well-being

By achieving these goals, i-Tree users can create healthy, sustainable, and resilient forest landscapes across the urban-to-rural continuum.


Tools

i-Tree tools aid in forest management decisions, education, and advocacy by working at various scales: from the individual tree, to the property, neighborhood, city, and landscape levels. The tools are divided into five categories:


- 🌳 **Core Programs** – fundamental tools that assess forest tree populations, ecosystem services, and values. These main programs are designed to provide forest data and aid in improving forest management decisions. The core programs¹ are known as:
 - ✿ i-Tree Eco
 - ✿ i-Tree Design
 - ✿ i-Tree Landscape
 - ✿ i-Tree Canopy
 - ✿ MyTree
 - ✿ Our Trees
- 🌳 **Utilities** – stand-alone utilities that aid the core programs or are specialized applications for specific purposes. The utilities are:
 - ✿ i-Tree Species
 - ✿ i-Tree Database
 - ✿ i-Tree Projects
 - ✿ i-Tree Glossary
 - ✿ i-Tree Eco Mobile Data Collection
 - ✿ i-Tree Trillion Trees
- 🌳 **Partner Tools Powered by i-Tree** – these are tools developed for specific partners that available for all to use. These tools are:
 - ✿ County Tree Benefits

¹ Core programs and utilities listed here are current as of December 2023.

- ✎ GHG Planting Calculator
- ✎ Harvest Carbon Calculator
- ✎ Wood Marketplace

 **Research Programs** – the code to research programs are available for advanced, technical users. Results from these tools are often built into core i-Tree tools to make this research more accessible to broad audiences. Technical support is not available for these tools. Research tools are:

- ✎ i-Tree Cool River
- ✎ i-Tree Hydro+
- ✎ i-Tree Cool Air
- ✎ i-Tree Energy

 **Legacy Programs** – programs that have been incorporated within other tools or utilities, or are no longer being updated by i-Tree. Original versions of these programs, except for the Mobile Community Tree Inventory (MCTI) program, can still be used and are available on the i-Tree Website:

- ✎ i-Tree Streets (incorporated within i-Tree Eco)
- ✎ i-Tree Vue (superseded by i-Tree Landscape)
- ✎ Mobile Community Tree Inventory (MCTI) (incorporated within i-Tree Eco)
- ✎ i-Tree Storm
- ✎ i-Tree Hydro
- ✎ i-Tree Pest

The programs and utilities are comprised of desktop (DT) and web-based (web) applications.


CORE PROGRAMS


Eco (DT) uses sample or inventory data collected in the field along with local hourly air pollution and meteorological data to assess forest structure, health, threats, and ecosystem services and values for a tree population. Information provided to the user includes number of trees, diameter distribution, species diversity, potential pest risk, invasive species, air pollution removal and health effects, carbon storage and sequestration, storm water runoff reduction, VOC emissions, wood products, leaf nutrients, allergenicity index, and effects on buildings' energy use. Features of i-Tree Eco include:


- ✎ Plot selection programs.
- ✎ Manual data entry or mobile device data entry.
- ✎ Existing inventory import capability.
- ✎ Table and graphic reporting and exporting.
- ✎ Automatic report generation.
- ✎ Ability to forecast *future* tree population totals, canopy cover, tree diversity, tree diameter distribution, and ecosystem services and values by species based on user-defined planting rates and default or user-defined mortality rates (e.g., a user can simulate the effects of emerald ash borer by specifically killing off ash trees).




[Design](#) (web) links to Google maps and allows users to see how the trees around their home affect various environmental services. Users can use this tool to assess which locations and tree species will provide the highest level of benefits. This tool is geared toward homeowners, students, or anyone interested in tree benefits. Additional capabilities include multiple tree and building placements, projecting future and past benefits, and displaying preferred planting zones.


[Landscape](#) (web) integrates national land cover, population, and environmental data to aid in forest management and planning. This tool features:

















 National data layers related to landscape structure

-  tree canopy
-  land cover
-  forest basal area by species
-  forest type
-  basic census information
-  impervious cover
-  bird species richness
-  endangered species count

 Ecosystem services and values from trees

-  carbon storage and annual sequestration
-  air pollution removal
-  hydrologic effects

 Risks to forest and human health

-  air pollution exposure
-  areas of poor air quality
-  brownfields
-  cumulative drought severity index
-  flood and riparian zones
-  future hardiness and heat zones
-  future ozone concentrations
-  hardiness zones
-  hurricane storm surge
-  impaired waterways
-  insects and diseases
-  impaired waterways
-  projected future climates
-  projected urban development
-  street walkability
-  surface temperatures

- ✎ tree species shifts due to climate change
- ✎ ultraviolet radiation exposure
- ✎ water quality index
- ✎ wildfire potential
- ✎ wildland urban interface changes
- ✎ wildland urban interface zones

Users can select their area of interest to explore these multiple datasets and weight the data to prioritize areas for management actions (e.g., most important areas to plant or protect trees). i-Tree Landscape is a web-based tool that can improve forest management and planning, and engage stakeholders in management prioritizations and decisions to improve forest and human health and sustainability.

[Canopy](#) (web) allows users to easily photo-interpret Google aerial images to produce statistically reliable estimates of tree and other cover types along with calculations of the uncertainty of their estimates. This tool provides a quick and inexpensive means for cities and forest managers to accurately estimate their tree and other cover types. Canopy can be used anywhere in the world where high-resolution, cloud-free Google images exist (most areas). Use of historical imagery can also be used to aid in change analyses.

[MyTree](#) (web) is a mobile phone application (app) that allows users to rapidly quantify the benefits and values of individual or small groups of trees (Fig. 1).

[OurTrees](#) (web) allows users to quickly explore the benefits provided by the tree canopy cover across their community.

UTILITIES

[Species](#) (web) helps users select the most appropriate tree species based on desired environmental functions and geographic area. The program calculates the best tree species based on user-provided weighting of desired environmental benefits at maturity.

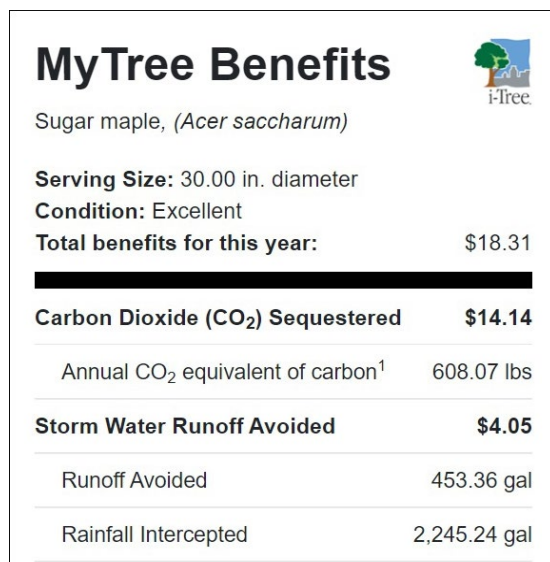


Figure 1.—MyTree report screen

[Database](#) (web) allows international users to submit local city, pollution, and precipitation data to be integrated into i-Tree. Once integrated, typically within a few months after being submitted, users can run i-Tree Eco for that international location. Users can also view and submit new tree species information to help build a global tree database.

[Projects](#) (web) allows users to visualize the plot and community data, as well as download the actual field data for further analysis and contrast data among communities.

[Glossary](#) (web) provides an reference for terms used in i-Tree.

[Eco Mobile Data Collection](#) (web) is a data collection system designed to work with newer web-enabled mobile devices.

PARTNER TOOLS POWERED BY I-TREE

[Planting](#) (web) is designed to help estimate the long-term environmental benefits of a tree planting project.

[Harvest](#) (web) allows land managers to estimate the amount of carbon stored in harvested wood products (originally known as the PRESTO Wood Calculator).

[County](#) (web) assesses the benefits for an area within a U.S. county or for the entire county.

[Wood Marketplace](#) (web) is a “Craigslist” for removed trees that connects urban wood harvests to end users of removed trees for upcycling and waste reduction.

RESEARCH PROGRAMS

[Hydro+](#) (DT): a combination of i-Tree Hydro (semi-distributed and fully distributed versions) and i-Tree Cool Air (fully distributed), which is an air temperature model simulating the effects of land cover changes using i-Tree Hydro’s water budget and an energy budget that explicitly accounts for vegetation processes. This model includes the i-Tree Cool River and Cool Air models. Cool River simulated the effects of riparian shading and impervious runoff on river water temperatures. Cool Air simulates the effects of tree and impervious cover on air temperatures.

LEGACY PROGRAMS

[Streets](#) (DT) is similar to Eco but focuses on street tree populations using regional reference city street tree data. Features of this program have been incorporated within i-Tree Eco. Street tree analyses within Eco do not use reference city data but rather use local pollution and weather data to estimate ecosystem services.

[Vue](#) (DT) is the precursor program to i-Tree Landscape. It has now been superseded by the i-Tree Landscape program, which is more accessible and uses newer data with more modeling capabilities.

[Mobile Community Tree Inventory](#) (DT) is a basic tree inventory application designed for use with a personal digital assistant (PDA). This program has been incorporated within the mobile data collection feature of i-Tree Eco. This original PDA application is no longer distributed or supported.



Figure 2.—i-Tree results have been used in innovative ways to convey the benefits of trees.

Storm (DT) helps assess widespread street tree damage in a simple and efficient manner immediately after a severe storm. It is adaptable to various community types and sizes and provides information on the time and funds needed to mitigate storm damage.

Hydro (DT) simulates the effects on hourly stream flow and water quality due to changes in tree cover and impervious cover within a watershed. It contains auto-calibration routines to help match model estimates with measured hourly stream flow.

Pest Detection (IPED) (DT) provides a portable, accessible, and standardized method of observing a tree for possible insect or disease problems within i-Tree Eco.

All programs, except for MCTI, are available and free, including technical support for all core programs, online training, user's manuals and resources, and a moderated peer-to-peer online forum.

Partnerships

The core partners in i-Tree development, dissemination, and support are the USDA Forest Service, Davey Tree Expert Company (Davey Tree), Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, and SUNY College of Environmental Science and Forestry. In addition, several Federal and university personnel are involved with developing new parts to i-Tree and/or providing data and information used within i-Tree.

For more than 20 years, the USDA Forest Service and Davey Tree have collaborated on cooperative research and development to improve understanding and management of trees and forests. Davey Tree matches USDA Forest Service funding and has jointly-funded employees within USDA Forest Service and Davey Tree offices who work on i-Tree development, dissemination, and support. Through this relationship, and with the help of numerous other cooperators, the i-Tree software suite is developed and now serves as a premier, state-of-the-art, peer-reviewed toolset for assessing forest ecosystem services and values (Fig. 2).

As integral partners, the USDA Forest Service and Davey Tree signed a Memorandum of Understanding in 2015 to strengthen their cooperation through an expanded relationship with the following goals:

- ✿ Continue cooperating to develop, maintain, disseminate, and support the i-Tree suite of assessment tools.
- ✿ Expand the geographic focus of i-Tree to include all landscapes, both public and private, and rural and urban.
- ✿ Contribute to a collaborative discussion that aims to improve the health of our urban forests and our nation's forests as a whole.
- ✿ More effectively deliver a growing scientific-based body of knowledge of trees and ecosystem services to a broader, more diverse set of stakeholders and geographies.
- ✿ Explore how mutually beneficial research and development can be better utilized in traditional forest management and in managing emerging threats such as climate change, invasive pests, and increasing wildfire size and severity.
- ✿ Engage youth and educators in the use of i-Tree to learn about forest dynamics, ecosystem services and their value, the wonder of nature, the importance of stewardship, and to encourage a greater appreciation for the natural environment within our next generation of conservation leaders.

History

The origin of the i-Tree program is the USDA Forest Service's Urban Forest Effects (UFORE) model, which was developed in the 1990s, and the Street Tree Resource Assessment Tool for Urban Forest Managers (STRATUM) model, which was released in the early 2000s. Both of these programs were built from research originally developed in the USDA Forest Service's Chicago Urban Forest Climate Project (McPherson et al. 1994; Nowak 1994a, 1994b, 1994c). UFORE also had its origin from work in Oakland, CA (Nowak 1991). Due to user confusion between these closely related programs, a decision was made to integrate USDA Forest Service urban forestry tools within one program. This program was named "i-Tree"² and first released in 2006. The programs were originally designed to aid in urban forest management but have since been expanded to meet the needs of multiple constituents, including rural forest managers, consultants, planners, homeowners, educators, and landscape professionals. The research and work of numerous people were instrumental in the evolution of i-Tree ([appendix 1](#)).

I-TREE TIMELINE

- ✿ 1988–1991—Assessment of Oakland, California (original methods developed).
- ✿ 1991–1994—Chicago Urban Forest Climate Project (methods refined).
- ✿ 1996—UFORE model released.
- ✿ 2004—STRATUM model released.
- ✿ 2005—i-Tree partnership formed between primary cooperators, USDA Forest Service and Davey Tree, leading to the development of a new, cohesive platform for delivering urban forest science and technology. This platform would become i-Tree and bring together research, scientists, and stakeholders in a coordinated

²The name i-Tree was derived from the concept of: Integrated Tree Resources – Environmental and Economic.

effort to offer the urban forest community increased access to technology-based assessment tools. An executive leadership committee of stakeholders provides program guidance and additional in-kind resources.

- ✿ 2006—i-Tree version 1.0 released (UFORE and STRATUM programs, Mobile Community Tree Inventory, and Storm Damage Assessment utilities).
- ✿ 2007–2009—i-Tree versions 2.0 and 3.0 released, with updated programs and new features, including automatic report generation, added help menus, and updated manuals; web-based download and installation; release of i-Tree Species and Vue; programs renamed (e.g., UFORE became i-Tree Eco, STRATUM became i-Tree Streets) for consistency.
- ✿ 2010–2011—i-Tree usage grows to nearly 10,000 and has significantly expanded applications, delivering scalability from single tree to landscape level analysis; i-Tree Design, Canopy, and Hydro were introduced as new core tools to reach new audiences: landscape architects, commercial landscape professionals, arborists, engineers, nonprofits, teachers, and planners.
- ✿ 2012–2014—i-Tree version 5.0 adds updated features. i-Tree Design additions include forward and backwards projections of benefits, and multiple tree and building analyses; i-Tree Canopy additions include ecosystem services and values, and cover change analysis capabilities; and i-Tree Eco additions include new services, values, risks, and health benefits. The Energy Saving Trees™ program (<https://energysavingtrees.arboday.org/#Home>) broadens dissemination of i-Tree models to homeowners through Utility provider engagement.
- ✿ 2015—i-Tree version 6.0 is released with new tools and functionality, including a new web-based spatial application called i-Tree Landscape and an i-Tree forecasting model integrated within a completely modernized i-Tree Eco application interface; i-Tree Eco is now also completely functional in Canada, Australia, and the United Kingdom.
- ✿ 2016—i-Tree version 2017 is released with the new MyTree app; new map layers and data in Landscape; and UV radiation reduction due to trees, expanded tree hydrology effects, and tree effects on wildlife habitat (nine bird species) added to Eco. i-Tree Species is moved to a new web-based application. i-Tree usage grows to more than 180,000 users globally.
- ✿ 2017—i-Tree version 2018 released with new i-Tree Database program to aid international users and facilitate international projects; i-Tree apps are expanded to include a new tree planting benefits calculator and a wood products calculator; many new map layers are added to Landscape; Hydro is updated with an improved user interface and help text, more flexibility in model inputs and outputs, and easier data format requirements to facilitate international use.
- ✿ 2018—i-Tree version 2019 released with i-Tree Eco versions for Mexico (en Español) and Europe; i-Tree education curriculum for grades 3-12; pollution removal by grass in i-Tree Eco; new i-Tree Landscape maps (impaired waterways, flood plains, riparian buffers, brownfields, street walkability, projected urban development, projected changes in species suitability due to climate change); and three new applications: i-Tree County, Projects, and Wood Marketplace.

- ✿ 2019—i-Tree version 2020 released with i-Tree Eco versions for Colombia and South Korea and new mapping capabilities; new i-Tree Landscape maps (threats to water quality, counts of threatened and endangered species, bird species richness, projected sea level rise, storm surge, future hardiness zones, future heat zones, wildland urban interface), new query function capabilities and high-resolution tree cover maps; upgraded interface for i-Tree Canopy and standard geographies added; release of i-Tree Cool River and Hydro+; new mobile-friendly website design.
- ✿ 2020—i-Tree version 2021 released with redline data in i-Tree Landscape; updated science and new international data in i-Tree Eco; prototype tree pinning function and database in MyTree; modernization of i-Tree Canopy that includes a new interface and outputs, color-coded maps, and standard national project boundary files.
- ✿ 2021—i-Tree version 2022 released with updated science and new international data; new reporting options in i-Tree Eco (allergy index, leaf nutrients and wood products); species database improvements; addition of PM10 reporting; air quality health impact and values reporting.
- ✿ 2022—i-Tree version 2023 released with i-Tree Eco versions for Japan, New Zealand, and Ukraine; updated science and new international data; 2020 pollution and weather data; added ability to import plot sample inventories; updated pest range data and inclusion of new pests; hydrology reporting added to Forecast; release of OurTrees tool.

i-Tree 2023

With the expansion of programs and partners, i-Tree usage has substantially grown both nationally and internationally. As of the end of 2023, there have been more than 910,000 users of i-Tree products in 94 percent of countries globally (Figs. 3 and 4). Usership increased 24 percent (100,000 new users) in 2020 (Fig. 5). The i-Tree website supports approximately 12,000 unique visitors each month (Fig. 6).

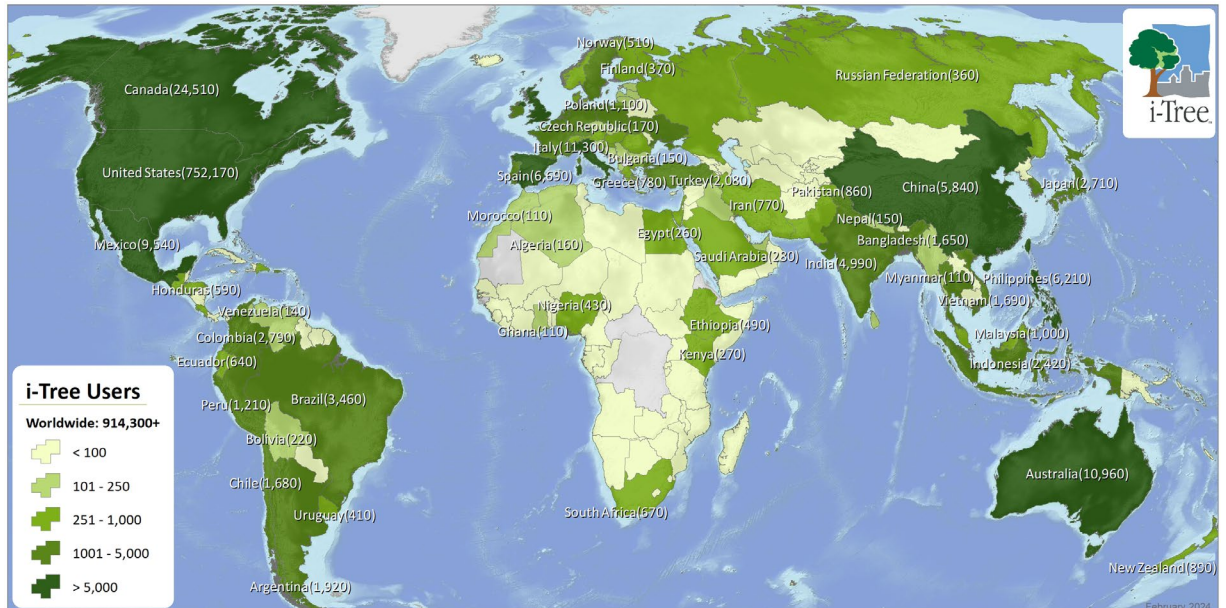


Figure 3.—Number of unique users of i-Tree and i-Tree dependent programs by country as of December 2023.

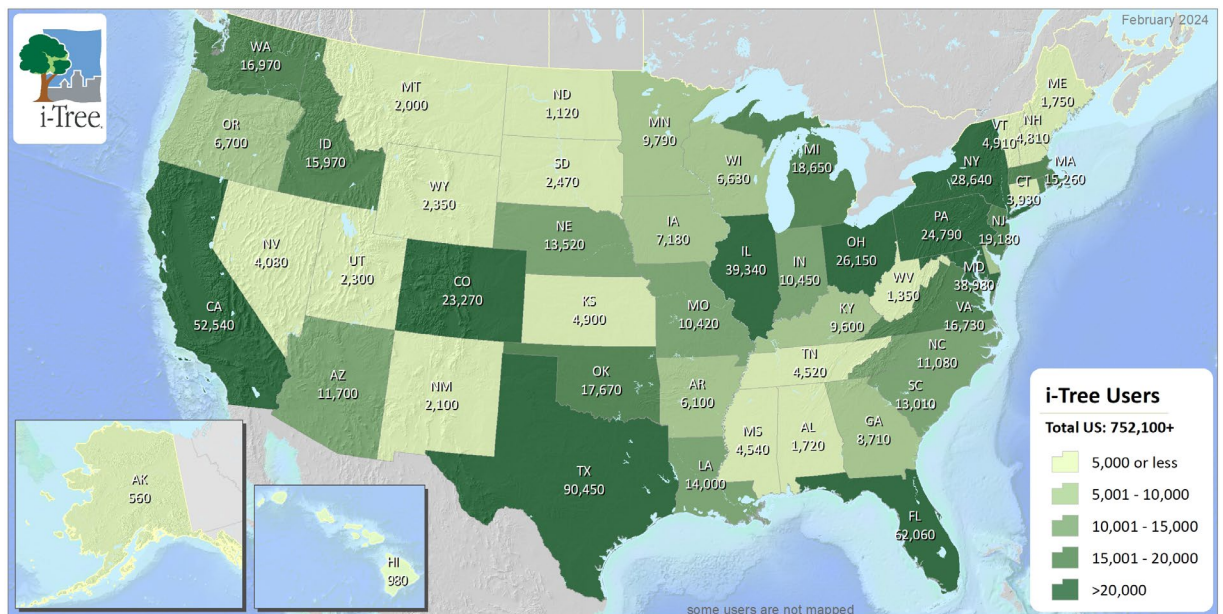


Figure 4.—Total i-Tree users by state as of December 2023.

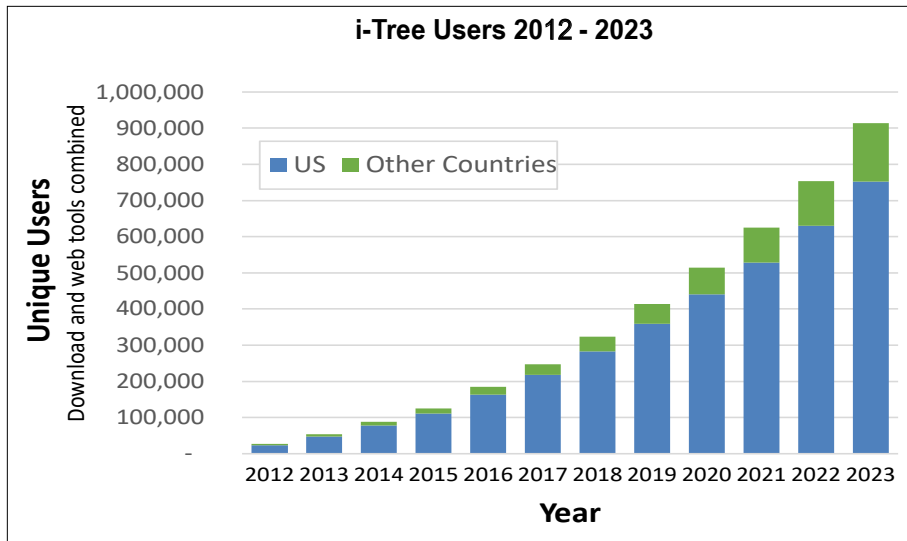


Figure 5.—Cumulative i-Tree usership by year (2012–2023). i-Tree added more than 160,000 new users in 2023, an increase of 24 percent.

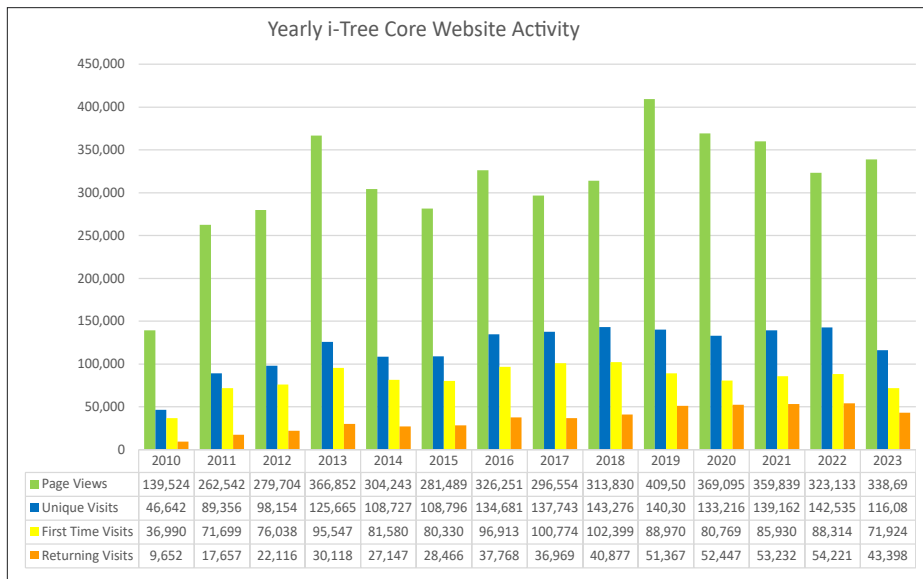


Figure 6.—i-Tree website (www.i-treetools.org) activity by year. In 2023, the website had approximately 12,000 unique visitors per month with over 54,000 returning visitors utilizing the website multiple times over the course of the year.

The information provided by i-Tree software has been used to influence management and policies throughout the United States and the world in relation to urban forestry. i-Tree results have been used by consultants, managers, and local citizens to guide management and policy decisions related to issues such as: emerald ash borer protection; building financial support for urban forestry programs, tree planting, and management; linking local tree data with the U.S. Conference of Mayors Climate Protection Agreement; public outreach campaigns (e.g., billboards, “price tags”; see Fig. 2) on tree benefits; developing Urban Forest Strategic Management Plans; and focusing funds to improve stewardship (Driscoll et al. 2012). The i-Tree team released a survey (<https://www.surveymonkey.com/r/iTreeSurvey>) for users to help improve the program and to learn more about success stories related to using i-Tree information. Numerous links and dependencies to i-Tree programs exist ([appendix 2](#)).

i-Tree and Urban FIA

The USDA Forest Service’s Forest Inventory and Analysis (FIA) Program provides critical information needed to assess the status, trends, and sustainability of the nation’s forests. In 2014, a national Urban FIA (UFIA; <https://www.fia.fs.usda.gov/program-features/urban/>) program began by integrating i-Tree into FIA. Since both i-Tree and UFIA fall within the bounds of the overall FIA program, there can be confusion between the two programs.

As stated previously, i-Tree is designed to estimate structure, ecosystem services, values, and risks to forests and people. Urban FIA is a national natural resources inventory system designed to monitor the quality, health, composition, and benefits of trees and forests within our nation’s urban land. UFIA has a goal of monitoring citywide tree data for approximately 100 of the nation’s most populous cities. To date, 45 cities have started monitoring (Fig. 7). More cities will be monitored in the future. Cities are monitored based on a panel system, where a proportion of total plots are analyzed annually. For example, in a 7-year panel, 1/7 of the total plots (~29 out of 200 plots) are analyzed each year, such that after year 7, all plots are measured. Year 8 rereasures year 1 plots, year 9 rereasures year 2 plots, and so on. Some cities, such as Austin (Nowak et al. 2016) and Houston, Texas (Nowak et al. 2017), have opted to collect all plots in year 1 and then start the panel-based

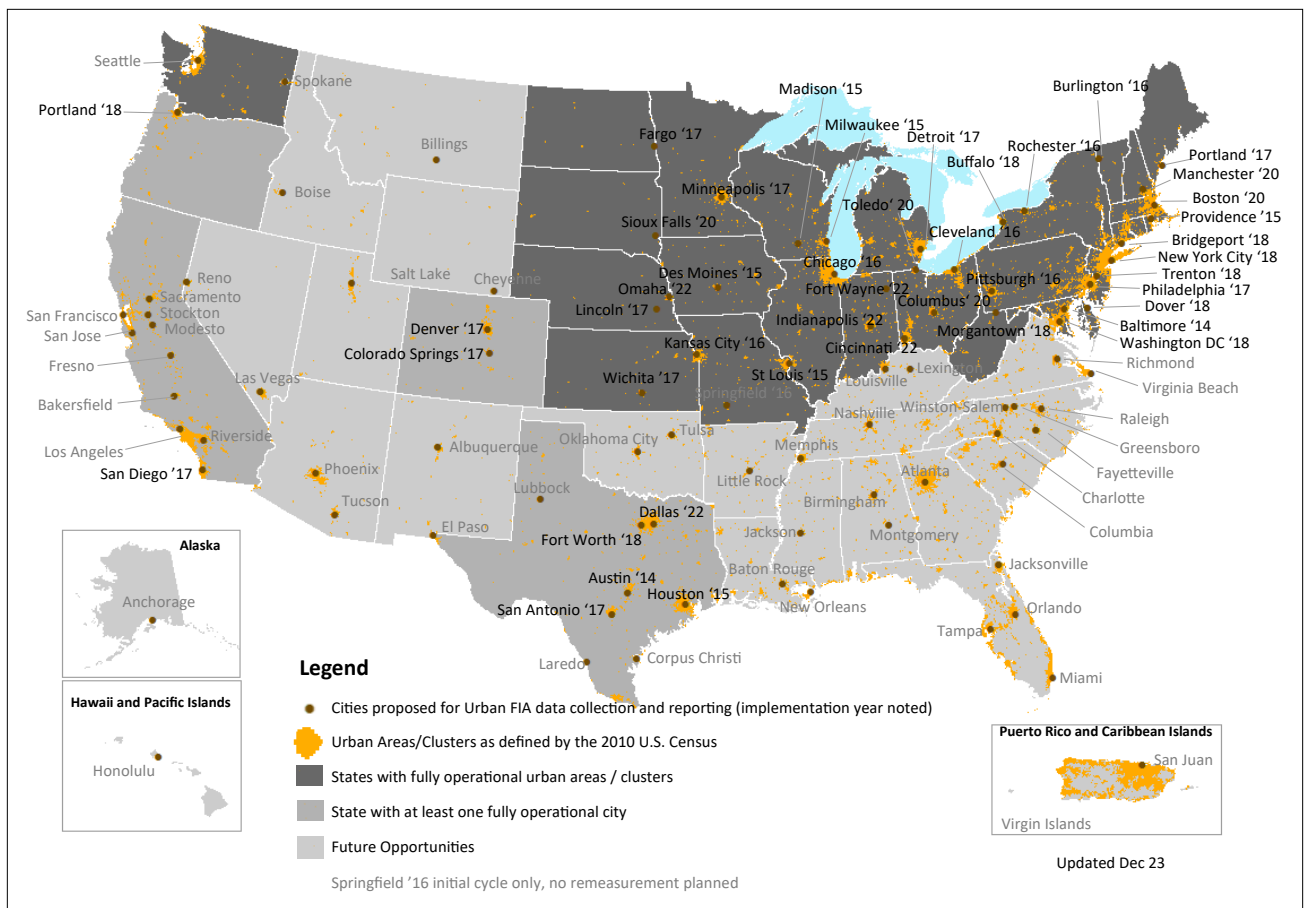


Figure 7.—Current and proposed cities to be monitored under the Urban FIA program and analyzed using i-Tree Eco as of December 2023.

resampling in year 2 to produce an assessment with all plots after the first year. Current cities being analyzed, by starting year, are:

- ✿ 2014: Austin, TX; Baltimore, MD
- ✿ 2015: Des Moines, IA; Houston, TX; Madison, WI; Milwaukee, WI; Providence, RI; St. Louis, MO
- ✿ 2016: Burlington, VT; Cleveland, OH; Chicago, IL; Kansas City, MO; Pittsburgh, PA; Rochester, NY; Springfield, MO
- ✿ 2017: Colorado Springs, CO; Denver, CO; Detroit, MI; Fargo, ND; Lincoln, NE; Minneapolis, MN; Philadelphia, PA; Portland, ME; San Antonio, TX; San Diego, CA; Wichita, KS
- ✿ 2018: Bridgeport, CT; Buffalo, NY; Dover, DE; Fort Worth, TX; Morgantown, WV; New York, NY; Portland, OR; Trenton, NJ; Washington, D.C.
- ✿ 2020: Boston, MA; Columbus, OH; Manchester, NH; Sioux Falls, SD; Toledo, OH
- ✿ 2022: Cincinnati, OH; Dallas, TX; Fort Wayne, IN; Indianapolis, IN; Omaha, NE

These cities are selected based on partnerships with local municipalities or states.

Urban FIA analyses are not limited to city boundaries, but also include the larger surrounding metropolitan landscape, complementing regional and local efforts to provide a cohesive picture of urban forest conditions across the United States. Urban FIA provides quality, publically available data for trees and seedlings that can be compared with rural forests regarding:

- ✿ Ecosystem services and values (via i-Tree)
- ✿ Tree volume, biomass, carbon, merchantability, and cull estimates
- ✿ Forest health (e.g., crown conditions and damage to trees)
- ✿ Forest change through time

Related to UFIA, i-Tree Eco:

- ✿ Was used in pilot testing of UFIA analyses since the late 1990s (Buckelew-Cumming et al. 2008; Nowak et al. 2007a, 2012).
- ✿ Analyzes the ecosystem services and values derived urban forest data collected in the UFIA program.
- ✿ Is being seamlessly integrated within FIA to optimize data processing and reporting of Urban FIA data and to allow for Urban FIA and i-Tree to produce similar outputs.

While i-Tree helps with national urban forest monitoring through FIA, it also helps anyone in conducting local forest analyses. If a community's urban forest is being assessed by UFIA, then that community will not need to run i-Tree Eco because i-Tree will be used on the FIA data to estimate these services and values. If UFIA is not collecting data in a community, i-Tree Eco can be used by a community to collect information on their local urban or rural forest and have results similar to Urban FIA analyses. There are also additional i-Tree tools that a community or individuals can use to conduct more localized assessments (e.g., rural forests, street trees, parks, back yard, single trees). Users can choose what i-Tree tool to use to best meet their local needs.

FUTURE GOALS

The overarching goal of the i-Tree program is to develop best management practice prescriptions based on local environmental and forest data. These prescriptions will aid managers in sustaining healthy and functional forests to improve human health and well-being. These management prescriptions will detail best tree species, locations, and planting rates to attain desired outcomes. The specifics of each prescription depend upon local site conditions and issues, and user's preferences. To attain this goal, the i-Tree team is focused on developing both i-Tree Eco and i-Tree Design as the tools that integrate the science and information from numerous sources in one system to aid managers (Fig. 8).

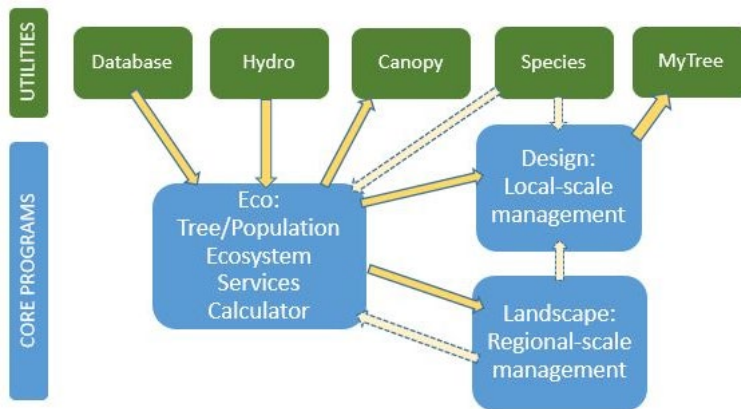


Figure 8.—Linkages between i-Tree programs and utilities. Arrows indicate the direction of passage of information or routines to subsequent programs. Dotted-line arrows indicate future linkages. i-Tree Design and i-Tree Eco will ultimately make forest management recommendations related to best tree species and locations to improve forest and human health given local conditions.

To reach this goal, the i-Tree team is currently focusing on developing more national map-layer information into i-Tree Landscape and more tree species-specific information within i-Tree Species. Upon completion of these two tools, the information in these tools will feed environmental quality and risk information (from Landscape) and species' abilities to provide environmental benefits (from Species) into Eco and Design to develop forest management guidelines. The suggested management prescriptions will include species recommendations, optimal locations, and planting rates needed to best address local environmental issues and risks, and to sustain a healthy forest into the future. For example, when a user enters data from a specific location, i-Tree will search the Landscape database for the area to determine the environmental issues and risks, potentially including poor air quality, high UV radiation, insect and disease threats, and future species performances based on climate change. Knowing these issues, i-Tree will search the species database and suggest the best species given the current issues and risks. For example, if the area has poor air quality and Emerald ash borer, the prescription will suggest the best species for improving air quality that are not ash trees. The prescription will also suggest landscape designs, planting locations and planting rates to sustain current or desired levels of tree cover throughout the landscape. Future development and integration of tools is critical to meeting this management prescription goal.

While this management prescription tool is the overarching goal, there are 10 specific goals that i-Tree intends to attain over the next 5 years (2020 to 2025):

1) Maintain quality programs – This work is essential and involves keeping software and servers functional and bug-free. With growing programs, usage, and constantly changing software (e.g., Microsoft® Windows operating systems, Internet browsers), continuous

maintenance is essential. The code for older tools will be released through an i-Tree legacy site and will no longer be supported; core tools and utilities will be maintained on the i-Tree site; and new tools (see #2 below) will be released on an i-Tree Research site once these tools have been tested and passed peer review.

2) Integrate more ecosystem services and values – Currently many new ecosystem service calculations are in development, including tree effects on air temperatures (Yang et al. 2013), human comfort, green infrastructure effects, forest bathing, wood products, and pollen. Once research on these new services passes peer review, they will be incorporated within the core i-Tree tools or released through the i-Tree Research development site as appropriate. This work will be useful for ecosystem/natural capital accounting.

3) Increase connections to human health and environmental regulations – Links with air quality and human health already exist in i-Tree; working with numerous cooperators, the i-Tree team is working to add additional connections to human health related to air temperature, ultraviolet (UV) radiation, and stress reduction. i-Tree staff continues to try and link i-Tree outputs with environmental regulations.

4) Enhance i-Tree Landscape – Based on numerous national datasets from several cooperators, this tool will be adding many features, including national map data related to:

- ✿ Forest fragmentation
- ✿ Heat islands
- ✿ Potential hurricane damage

To create healthy and resilient forests that provide optimal services for people, it is important to determine the best locations for trees within the landscape. To do this, four factors are being considered:

- ✿ Human and forest population distribution
- ✿ Locational differences in ecosystem service production
- ✿ Risks to human health (e.g., air and water pollution, temperature, climate change, flooding, UV radiation exposure)
- ✿ Risks to forest health (e.g., insect and diseases, climate change, urban development, fire)

In addition to data that aid in assessing locations with the highest risks to forests and/or humans, other new features will be added, including new querying and prioritization capabilities and increased map resolution.

5) Improve capabilities of i-Tree Species – This program is designed to determine the best tree species for desired ecosystem services. This program will be enhanced by expanding and enhancing species information to aid users in making species selections and improving environmental quality.

6) Increase functionality of i-Tree Design/My Tree – These programs are designed to easily calculate effects of small tree populations by allowing users to estimate the benefits and values of individual trees. i-Tree Design will be enhanced by linking to data in i-Tree Landscape and new ecosystem services in i-Tree Eco that are being developed. The MyTree phone app (Fig. 9) is being linked to the i-Tree Trillion Trees site to allow people to map trees globally.

7) Full integration of i-Tree tools within FIA – The i-Tree team, which is part of the USDA Forest Service’s Forest Inventory and Analysis (FIA) program, is working closely with the Urban FIA team and other FIA groups to integrate i-Tree seamlessly within FIA processes. This integration will allow for rural forest estimation of many ecosystem services and values that are now only typically available for urban forests (e.g., air pollution removal).

8) Increase utility of tools for National Forests and State Forests – i-Tree Landscape and other tools have capabilities to aid in national and state forest management. By working with national and state forest staff, tools will be enhanced or modified to address regional scale forest issues and management needs.

9) Enhance School Educational Curriculum using i-Tree – i-Tree staff are working with USDA Forest Service Conservation Education, Project Learning Tree, and others to develop student and teacher guide books and curriculum (www.itreetools.org/support/resources-overview/welcome-i-tree-teaching-resources) to facilitate the use of i-Tree to teach science in schools.

10) Expand international partnerships – i-Tree tools have the capability and are being used internationally, but the tools are often not specifically designed to work internationally. Thus, developing international partnerships (<https://www.itreetools.org/support/resources-overview/i-tree-international>) to facilitate the development and use of i-Tree is critical to sharing and enhancing the global use of the tools.

The development of i-Tree has expedited urban and rural forest data collection and analysis across the world (Fig. 10). This international data collection is providing valuable new data to aid research in understanding patterns and variations in forests and the ecosystem services and values they provide. New i-Tree versions are being developed for select cities in other countries via i-Tree Database. i-Tree serving as a global standard on data collection and analyses will facilitate further research and comparison on forests worldwide.



Figure 9.—MyTree report screen.

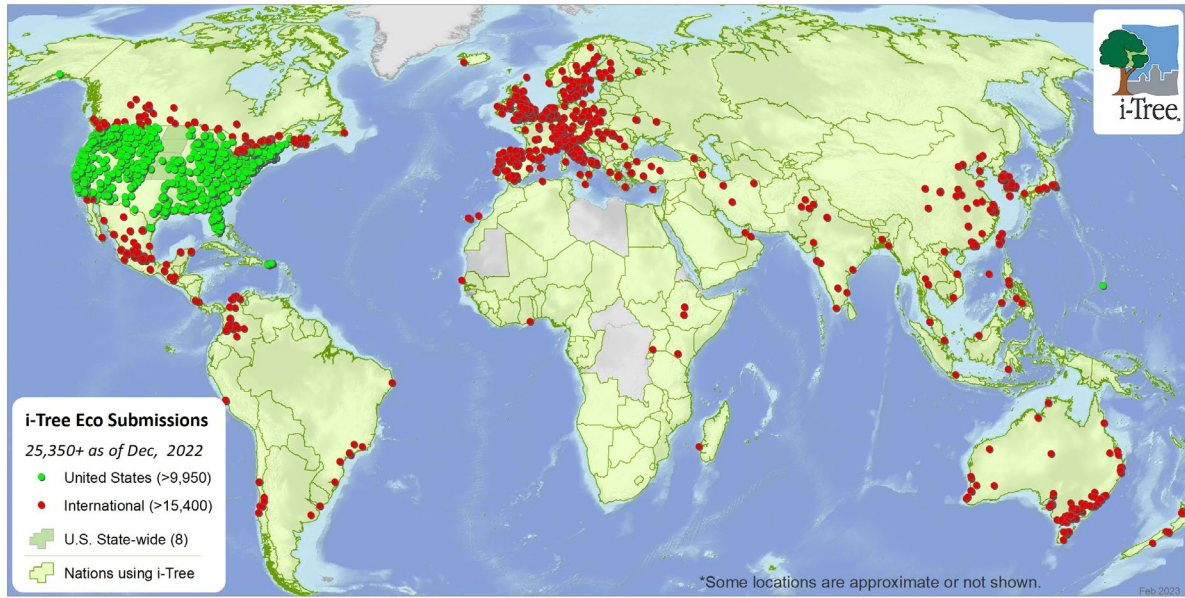


Figure 10.—Known i-Tree Eco projects as of December 2022.

METHODS, ADVANTAGES, AND LIMITATIONS

The premise behind i-Tree is shown in Figure 11. Structure is the basic information on the physical forest resource (e.g., number of trees, species composition, tree sizes and locations, leaf area, etc.). The attributes are directly measured by users or estimated (e.g., leaf area) by i-Tree based on direct measures of structure. From the structure data, along with local environmental data (e.g., weather data), various tree functions (e.g., gas exchange, tree growth) are estimated. These functions are then converted to various services (e.g., pollution removal) based on other local data (e.g., pollution concentrations). These services are then converted to benefits (e.g., cleaner air, impacts on human health) based on other data (e.g., local atmospheric conditions, human population data). Finally, the benefits are converted to values based on various economic procedures.

Forest management objectives often seek to improve environmental or human health, or the value of the forests. Forest managers do not directly manage functions or values, rather they manage forest structure (i.e., plant and remove trees, protect existing forests, and select species and locations) to optimize services and values. However, managers are not the only force influencing forest structure. The existing forest and the environment have a substantial influence on forest structure through natural regeneration, tree growth and mortality, storms, insects and diseases, invasive plants, and other factors. Included in this environmental influence are unintended consequences of human actions and development (e.g., introduction of exotic plants, insects and diseases, increased air temperatures and pollution, climate change, etc.). People and nature act to alter forest structure and consequently forest services and values.



Figure 11.—Diagram showing basic i-Tree process.

i-Tree is designed to aid managers by providing basic data on forest structure, services, and values. The i-Tree team is also working on providing management guidance related to the best species and locations to sustain or enhance forest health, services, and values through time. There are four main steps needed to quantify the services and values from forests (Nowak 2018):

- 1) Quantify the forest structural attributes that provide the service for the area of interest (e.g., number of trees, tree cover). These structural data are essential as they quantify the resource attributes that provide the services.
- 2) Quantify how the structure functions and influences the ecosystem service (e.g., tree density, tree sizes, and forest species composition are significant drivers for estimating carbon storage).
- 3) Quantify the benefit of the selected ecosystem service. In many cases, it is not the service itself that is important, rather the impact that the service has on human health or other environmental attributes that provide value to society.
- 4) Quantify the economic value of the impact provided by the ecosystem service.

Given the framework illustrated in Figure 11, it is imperative that forest structure be accurately assessed. Inaccurate measurement of structure will lead to inaccurate estimates of subsequent services and values. Similarly, the validity of the models and data that are used to estimate services and values will impact that accuracy of these estimates. As with any assessment and modeling framework, there are tradeoffs among selected methods in terms of efficiency, cost, practicality, and accuracy. All current estimates and means of estimation can be improved to varying degrees.

The following section will discuss the basic methods used to assess forest structure in i-Tree along with advantages and limitations of the approaches used. Additional sections will introduce the methods used convert those structural assessments into estimates of services and values. This report may not provide full details but will reference documents and research that contain the full methods. Additional sections will also detail how various i-Tree tools beyond i-Tree Eco assess structure, services, and values. The methods detailed here correspond to i-Tree 2023 (version 6.1.47).

Assessing Forest Structure in i-Tree Eco

Good forest structure data are critical to i-Tree. These data can vary from information about an individual tree to consolidated information about the entire urban forest. Forest population data can be derived either from an inventory of the population, where all trees are measured, or from a sample of the population, where some subsets of the population are randomly selected and the population total is estimated from this sample.

Before taking the sample, land managers can decide whether the data will be collected with a certain number of plots in each land use type (e.g., prestratified), or collected randomly from plots and later categorized by land use type (e.g., post-stratified). Prestratification can reduce the statistical variance and allow users to put more plots in desired strata (e.g., putting more plots within forested urban areas). However estimates of change through long-term monitoring of the plots is complicated as the strata can change through time. With post-stratification, the randomly located plots can be reclassified into most any strata classification after data collection (e.g., land use, management zones). This post-

stratification may not be the most efficient in reducing variance but allows for easier assessments of change.

With an inventory of all trees, there is no estimate of variance or sampling error in the population total as the entire population is inventoried. With sampling of a subset of trees, the standard error of the population estimate is calculated.

Users can select which assessment method is most appropriate for their population (i.e., inventory, prestratified sample, or random sample with post-stratification). Inventories likely work best for small populations of trees, or populations where intensive management is conducted on each tree (e.g., street tree populations). Quality assurance guidelines are provided in the i-Tree field manual (i-Tree Team 2019a) to help ensure that tree measurements are conducted and recorded properly in the field.

This section will detail what measurements are made or derived for each tree, how the estimate is derived, the uncertainty of the measure, and how the standard errors are calculated for population samples. This section and the next section, “Assessing Ecosystem Services” focus on methods used in i-Tree Eco, which is the core i-Tree computer program. Other i-Tree tools use derivatives of i-Tree Eco outputs (results) to assess ecosystem services and these derivative procedures are described later in this report. Field and user’s manuals are available in several languages to guide users in establishing projects, collecting field data, and operating the program. These manuals are updated regularly and available online. In this report, we refer to version 6.0 (7.2.2019) of the field and user’s manual (i-Tree Team 2019a, 2019c).

TREE MEASUREMENTS

i-Tree defines a tree as any woody plant with a diameter at breast height (d.b.h.; defined as the measurement at 1.37 m [4.5 ft] greater than or equal to 2.54 cm (1 inch)). A shrub is defined as any woody plant with a d.b.h. less than 2.54 cm. However, users can set their own classification of tree versus shrub (e.g., based on species). Table 1 summarizes the core variables directly measured for each tree. Other optional tree or site variables are detailed in the field manual (i-Tree Team 2019a).

Table 1.—Core tree variables used in i-Tree Eco

Tree Variables		Description
Species		Identify and record the species and genus names of each tree
D.b.h.		Exact measurement or categories of the tree stem diameter at breast height (1.37 m) for each tree
Total tree height		Height from the ground to the top (alive or dead) of the tree
Crown size	Height to live top	Height from the ground to the live top of the tree
	Height to crown base	Height from the ground to the base of the live crown
	Crown width	The width of the crown in two directions: north-south and east-west
	Percent crown missing	Percent of the crown volume that is not occupied by branches and leaves
Crown dieback		Estimate of the percent of the crown volume that is composed of dead branches
Crown light exposure		Number of sides of the tree receiving sunlight from above (maximum of 5)
Energy	Direction	Direction from tree to the closest part of the building
	Distance	Shortest distance from tree to the closest part of the building

For multi-stemmed trees, the d.b.h. for up to six stems can be recorded. If there are more than six stems, the d.b.h. is recorded below the fork and d.b.h. height is recorded so it can be remeasured at the same height in the future. For multi-stem trees, i-Tree calculates a single d.b.h. estimate as follows:

$$\text{Single d.b.h.} = (\text{BA}/0.00007854)^{0.5}$$

Where: BA = the total basal area³ of the stems (m²), and d.b.h. is measured in cm

Or

$$\text{Single d.b.h.} = (\text{BA}/0.005454)^{0.5}$$

Where: BA = the total basal area of the stems (ft²), and d.b.h. is measured in inches.

The tree characteristics are measured in the field and assumed to be measured without error. The i-Tree Eco User's Manual (iTree 2019c) describes how to collect these variables along with quality assurance procedures.

These measured characteristics are used to derive secondary structural variables and estimate various ecosystem services (Table 2). The secondary structural variables derived in i-Tree are leaf area, leaf biomass, leaf area index, and total tree biomass. Subsequently, the directly measured characteristics and derived variables are used to estimate ecosystem services (Table 2).

LEAF AREA AND LEAF AREA INDEX

The cumulative leaf area in an urban forest canopy is an important variable influencing estimates of biomass, air pollution removal, carbon storage and sequestration, and other ecosystem services.

Leaf area is defined simply as the amount of surface area (one-sided) of leaves on a tree. Leaf area measurements are “scaled up” to cover an entire urban forest. The cumulative amount of leaf area per unit of projected ground surface area is known as the leaf area index (LAI = leaf area (m²) / ground area (m²)).

Leaf area of individual open-grown, deciduous trees⁴ is calculated using a regression equation⁵ (Nowak 1996):

$$\ln Y = -4.3309 + 0.2942H + 0.7312D + 5.7217S + -0.0148C$$

³ Basal area is defined in this case as the total cross-sectional area of all stems at d.b.h. in the cluster.

⁴ Open-grown trees are defined as trees with a crown light exposure of 4 or 5 (see [Tree Measurements](#)).

⁵ Regression equation is used for deciduous trees with a crown height-to-width ratio of between 0.5 and 2.0; crown heights between 1 and 12 m, and crown widths between 1 and 14 m (see [Tree Measurements](#)). For trees with a crown height-to-width ratio (HWR) >2, the leaf area estimate is calculated by the regression equation based on the tree crown width and a HWR = 2. The tree's total leaf area is then calculated as the leaf area estimate × the tree's HRW/2. For trees with a crown HWR <0.5, a tree leaf area estimate is calculated by the regression equation based on the tree height and a HWR = 0.5. The tree's total leaf area is then calculated as the leaf area estimate × 0.5/HRW. For trees with dimensions beyond the end of the regression equation range (crown heights <1 m or >12 m or crown widths <1 m or >14 m), the leaf area is calculated by multiplying the ground area of the crown by the leaf area index (LAI) based on tree measurement at the end of the regression equation range. For example, once a crown height exceeds 12 m, the LAI for a 12 m crown height is determined based on the tree's actual crown width, height to width ratio, and shading coefficient; and this LAI is applied to ground area of the crown to determine the total leaf area.

Table 2.—Summary of which directly field-measured characteristics are used to estimate derived variables and ecosystem services. D= directly used; I= indirectly used; C= conditionally used.

	DERIVED VARIABLES		ECOSYSTEM SERVICES										
	Leaf Area	Leaf Biomass	Carbon Storage	Gross Carbon Sequestration	Net Carbon Sequestration	Energy Effects	Air Pollution Removal	Avoided Runoff	Transpiration	VOC Emissions	Compensatory Value	Wildlife Suitability	UV Effects
DIRECT MEASURES													
Species	D	D	D	D	D	D	I	I	I	D	D		
Diameter at breast height (d.b.h.)			D	D	D						D	D	
Total height	D	D	C	C	C	D	I	I	I	I		D	
Crown base height	D	D	C				I	I	I	I			
Crown width	D	D	C				I	I	I	I			
Crown light exposure			C	D	D								
Percent crown missing	D	D	C	C	C	D	I	I	I	I			
Crown health (condition/dieback)				D	D						D	D	
Field land use					D						D	D	
Distance to building						D							
Direction to building						D							
Percent tree cover						D	D	D				D	D
Percent shrub cover							D					D	
Percent building cover						D							
Ground cover composition							I					D	

Where

Y is leaf area (m²),

H is crown height (m),

D is average crown diameter (m),

S is the average shading factor for the individual species (percent light intensity intercepted by foliated tree crowns) (see [appendix 3](#)), and

C is based on the outer surface area of the tree crown ($\pi D(H+D)/2$).

The shading coefficient is an estimate of the percentage of sunlight striking a tree crown that is not transmitted through gaps to the ground ([appendix 3](#)). Trees with very dense crowns would permit less light to reach the ground, and thus have a high shading coefficient. If no shading coefficient is available for an individual species, the average

of shading coefficients from the other species' in the same genus is used. If no genus coefficient exists, then average family, order, subclass, or class coefficients are used. The coefficients, listed in [appendix 3](#), are based on McPherson et al. (2018).

When there is a percentage of the crown missing (percent missing), estimates of leaf area are adjusted downward by multiplying by:

$$1 - \text{percent missing (0-1)}.$$

If percent missing is not collected, then leaf area is adjusted by:

$$1 - \text{percent crown dieback (0-1)}.$$

More detailed methods are given in Nowak (2005) and Nowak et al. (2002b, 2008).

For a tree population assessment, two types of leaf area indices are calculated:

- 1) LAI_p: total population leaf area divided by total study area size, and
- 2) LAI_c: leaf area standardized per unit tree cover: $\text{LAI}_c = \text{LAI}_p / \text{percentage tree cover}$.

LEAF BIOMASS

Tree leaf biomass (weight of dry leaves) is calculated from leaf area estimates using species-specific conversion factors ([appendix 4](#)). Leaf biomass of shrubs is calculated as the product of the shrub crown volume occupied by leaves (m³) and measured leaf biomass factors (g/m³) for individual species ([appendix 5](#)). Shrub leaf area is calculated by converting leaf biomass to leaf area based on measured species conversion ratios (m²/g). Due to limitations in estimating shrub leaf area by the crown-volume approach, shrub leaf area is not allowed to exceed an LAI of 18. More detailed methods are given in Nowak et al. (2002b, 2008).

If no shading coefficient is found for an individual shrub species, the average coefficient from the species' genus is used. If no genus coefficients exist, then next higher phylogenetic level average is used as available.

TREE BIOMASS

Total tree dry-weight biomass for each measured tree is calculated using allometric equations from the literature ([appendix 10](#)). Only equations that produced whole tree carbon estimates within 2-14 t C at 100 cm d.b.h. are used. Where multiple equations were available for individual species, they were combined to produce one predictive equation for a maximum range of diameters. These combined species equations produced results that are typically within 2 percent of the project-wide estimates obtained by using the separate equations with more limited diameter ranges. Formulas were combined to prevent large changes in sequestration or storage estimates for consecutive diameter classes, which can occur when changing biomass equations. Equations that predict aboveground biomass are converted to whole tree biomass based on root-to-shoot ratio of 0.26 (Cairns et al. 1997) and 0.3 for palm trees (Singh et al. 2018). If multiple equations or equations that are not aligned with actual measured species are used, wood densities ([appendix 11](#)) of the actual species measured and the species equations were used to estimate biomass:

$$\text{Biom est} = \text{Biom eq} \times \text{WDspp} / \text{WDeq}$$

Where

Biom est = biomass estimate (kg),

Biom eq = Biomass estimates derived from equations (kg),

WDspp = wood density of the species measured, and

WDeq = average wood density from the carbon equations.

Open-grown, maintained trees tend to have less aboveground biomass than predicted by forest-derived biomass equations for trees of the same d.b.h. (Nowak 1994b). To adjust for this difference, biomass results for open grown trees with a crown light exposure value of 4-5 are multiplied by a factor 0.8 (Nowak 1994b). Since deciduous trees drop their leaves annually, only carbon stored in wood biomass is calculated for these trees.

If no biomass equation is found for an individual species, the average of results from equations of the same genus is used. If no genus coefficients exist, then next phylogenetic level average is used as available.

Estimates of leaf nutrients and values associated with annual leaf drop are estimated based on methods detailed in Nowak et al. (2019).

UNCERTAINTY IN TREE AND LEAF ESTIMATES

The estimation error in calculating leaf area, leaf biomass, and tree biomass is unknown, but model-derived estimates fall within range of measured values for forests and trees (e.g., Peper and McPherson 1998, 2003; Nowak et al. 2013a). The LAI_p values for various cities typically range between 0.3 and 2.2 (average = 1.1) (Nowak et al. 2008). The LAI_c average is 4.8 among measured cities (Nowak and Greenfield 2018). Typical LAI values for natural forests are 5–8 for deciduous forests and 9–11 for boreal conifer forests (Barbour et al. 1980). As urban forests are typically deciduous, 4.8 is a reasonable LAI value given the urban forest's more open structure (less vertical layering of trees, which decreases LAI). More leaf area to biomass conversion factors will be added to the i-Tree database based on McPherson et al. (2016). Leaf area estimation can likely be improved with more species-specific shading coefficients.

The biomass equations used in i-Tree have similar form and coefficient values to other carbon/biomass equations (Fig. 12). The average carbon density per unit of canopy cover in urban areas is 7.69 kg C/m², slightly larger than in forest lands (7.24 kg C/m²). However, the forest land estimate assumes 100 percent tree cover, which likely leads to an underestimate of carbon storage per unit of tree cover. i-Tree carbon densities are commensurate with estimates from numerous other studies (Nowak et al. 2013a).

As there are currently no urban tree biomass equations, forest-derived equations are used as proxies and should provide reasonable estimates as the tree diameter and height are measured. There are likely some differences in biomass between urban and forest-grown trees (e.g., McHale et al. 2009, Nowak 1994b), but more research is needed to determine actual differences or to develop specific equations for urban grown trees.

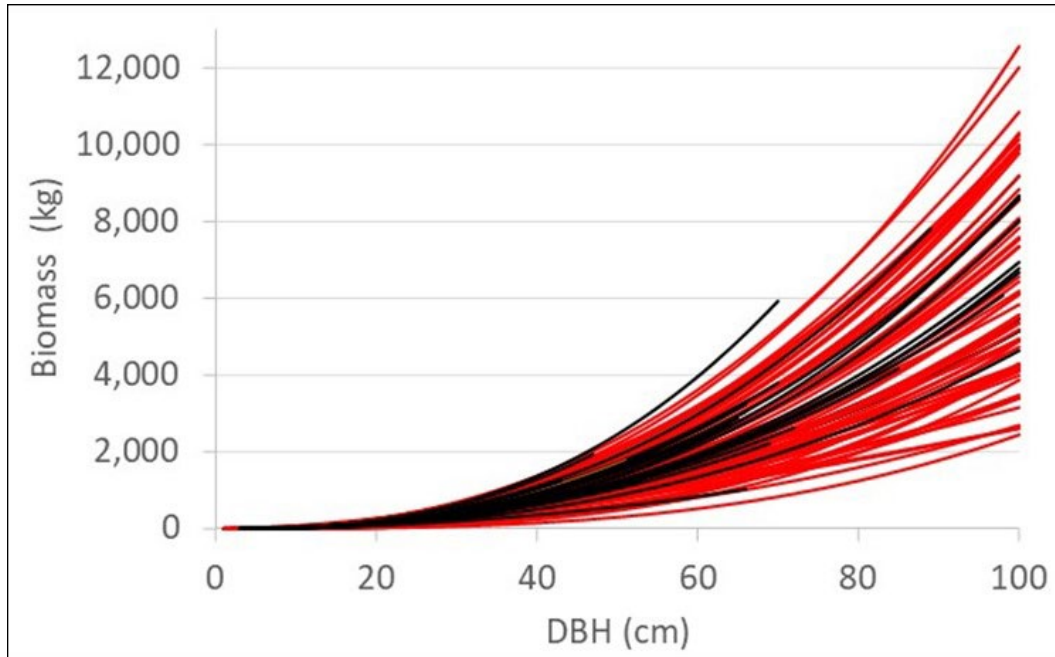


Figure 12.—Estimates of dry weight biomass for numerous species using various equations across a large diameter range. Red lines are i-Tree equation estimates ([appendix 10](#)); black lines are estimates from equations from Jenkins et al. (2003). Carbon estimates are one-half of dry weight biomass. When trees are small, equations estimates do not vary much. For large trees (d.b.h. = 100 cm [39.4 inches]), estimates of carbon range between about 1.2 t C to 5.9 t C, depending upon species equation. The equation estimates will not vary much as most of the urban forest is typically less than 15.2 cm (6 inches) d.b.h. However, for the fewer large trees, the estimates can vary by as much as fivefold.

Within i-Tree Eco, standard errors are reported for variables (leaf area, leaf biomass, tree biomass) that represent sampling error rather than error of estimation. As such, these sampling errors underestimate the total error of the estimates. Lack of information regarding errors in equations used to derive the secondary variables makes it impossible to fully account for estimation errors.

PLOT MEASUREMENTS

In addition to measurements on each tree, other measurements are taken for each sampled plot, including:

- ✦ Portion of plot measured (%)
- ✦ Tree cover (%)
- ✦ Shrub cover (%)
- ✦ Land use
- ✦ Ground cover types (%)

The percentage cover types are estimated to the nearest 5 percent class (e.g., 0–5%, 6–10%). While these estimates are fairly coarse, the precision of tree and other cover estimates can be improved through photo interpretation using i-Tree Canopy. This type of photo-interpretation is often used instead of field plot estimates due to the increased precision. With 1,000 random points, which can be interpreted in about 1 day, the standard error of the cover estimate will be less than 1.6 percent. Details on calculating

sampling error from photo-interpretation are given in Nowak (2011) and in the [i-Tree Canopy](#) section. More detailed information on plot sampling and measurements are given in the i-Tree Field Guide and User's Manual (i-Tree 2019a, 2019c).

SAMPLE TOTALS AND ERRORS


Sample totals and errors for metrics measured or derived from plot variables are based on standard statistical estimates of totals and variance from the plot data based on [formulas and procedures](#) detailed by a USDA Forest Service statistician.⁶

Assessing Structural Metrics and Risks in i-Tree Eco

TREE SPECIES DIVERSITY AND RANGE

i-Tree Eco estimates various tree species diversity indices and takes into account the native range of species.

Required Inputs

 Tree species

Methods Overview

The following indices are calculated for the living tree population in plot sample projects:

Shannon-Wiener Diversity Index is a widely used measure of diversity, based on information theory. This index assumes that the individual trees are randomly sampled from an infinite population. It also assumes that all species within a land use type or city have been sampled. This index is an indicator of species richness and has a moderate sensitivity to sample size (Magurran 1988) and, therefore, land uses and/or cities may not be comparable. The index is calculated as:

$$H' = -\sum_{i=1}^S p_i \ln p_i$$

Where

p_i is the proportion of trees in species i estimated as $\frac{n_i}{N} \cdot n_i$, and
 N is the total number of trees measured.

Menhinick's Diversity Index (D_{Mn}) is an indicator of species richness and has high sensitivity to sample size (Magurran 1988) and, therefore, may not be appropriate for comparison between strata with widely different numbers of plots. The index is calculated as:

$$D_{Mn} = \frac{S}{\sqrt{N}}$$

Where

S = number of species recorded, and
 N = total number of trees measured.

⁶ 1997 personal communication from David Randall, statistician with USDA Forest Service, Northeastern Forest Experiment Station, Radnor, PA.

Simpson's Diversity Index is an indicator of species dominance and has a low sensitivity to sample size (Magurran 1988) and, therefore, may be more appropriate for comparison among strata. The index is calculated as:

$$SI = 1/D$$

Where

$$D = \sum_{i=1}^S \left(\frac{n_i(n_i - 1)}{N(N - 1)} \right)$$

and where

S = number of species recorded,

N = total number of trees measured, and

n_i = number of trees of species i .

Shannon-Wiener's Evenness Index assumes that all species within a land use type or city have been sampled. It is an indicator of species evenness and has a moderate sensitivity to sample size (Magurran 1988) and, therefore, may not be useful for comparisons among strata or cities.

$$E = H' / \ln S$$

Where

H' = Shannon-Wiener diversity index, and

S = number of species.

Sanders' Rarefaction is a mathematical technique to standardize species richness from samples of several different populations with unequal sample sizes (e.g., different land use types within a single city) (Magurran 1988). This process is performed using rarefaction curves, i.e., scatter-plots of the number of species as a function of the sample size (i.e., the number of plots).

In i-Tree, strata (e.g., land use categories) represent the different populations, where each strata contains a different number of trees sampled. Rarefaction is stated as the number of tree species found within a standardized sample size over all strata (x species found from a sample of y individual trees). Typically, the standardized sample size is identical for each individual stratum (e.g., 10), but larger for the entire study area (e.g., 250). Sanders' Rarefaction is calculated as:

$$E(S) = \sum_{i=1}^S \left\{ 1 - \frac{\binom{N - N_i}{n}}{\binom{N}{n}} \right\}$$

Where

$E(S)$ = expected number of species,

n = standardized sample size,

N = total number of individuals recorded, and

N_i = number of individuals in the i th species.

Importance Value

Each tree species' importance value (IV) is calculated as the sum of the species contribution to the total tree population and leaf area.

$IV = (\text{percent of total number of trees comprised by a species} \times 100) + (\text{percent of total population leaf area comprised by a species} \times 100)$.

Native Status

The proportion of the tree population that originated from different parts of the United States and world was calculated based on the native range of each species (e.g., Burns and Honkala 1990a, b; Gleason and Cronquist 1991; Grimm 1962; Hough 1907; Little 1971, 1976, 1977, 1978; Platt 1968; Preston 1976; Sunset Books 1979; Viereck and Little 1975).

Economic Valuation

None. More research is needed on the value of species diversity and how it can be modeled and assessed in a local context.

Advantages, Uncertainties, and Limitations

Tree species diversity indices provide an indication of the diversity of the tree population only. They do not account for total biodiversity.

Comparing diversity indices among strata is fraught with pitfalls. Unequal sampling effort is a prime issue, where each strata not only has a different number of plots, but also different number of individual trees sampled. Many of these diversity indices show at least a moderate sensitivity to sampling intensity at both the area and individual scale (Magurran 1988). While rarefaction attempts to ameliorate this issue of sampling sensitivity, other techniques, such as jackknifing and the pooled quadrat method, may be used in the future. In addition, though each strata is randomly sampled with plots, there is no guarantee of randomness for the individual trees on those plots. Each individual diversity index has its own assumptions (listed under each diversity index above) that may be violated by i-Tree Eco as well.

Planned Improvements

✿ None.

POTENTIAL INSECT AND DISEASE EFFECTS

The risks to urban trees posed by 53 different insects and disease are estimated based on host-tree data and pest range maps in the United States. The 53 insects and diseases are listed in Table 3.

In addition to the risk the insect or disease poses to the tree's life, i-Tree Eco also estimates the impact to carbon storage and sequestration, leaf area and biomass, and structural value (Table 3). The model calculates the potential maximum impact on these tree variables and also categorizes the pests based on how far the pest is away from the study area.

Required Inputs

- ✿ Tree species
- ✿ D.b.h.
- ✿ Total height
- ✿ Height to crown base
- ✿ Crown width
- ✿ Percentage canopy missing: percent of crown volume not occupied by branches or leaves
- ✿ Crown dieback: percentage crown dieback in live crown area

Methods Overview

For each pest, [susceptible host tree species](#) were determined primarily from Liebhold (2010), with the Exfor database (Exfor 2014) serving as a secondary source. Other sources can be found in the [Tree Pest Host Data](#) Excel file (see tab labeled "Pest Host References".)

Range maps for each of the 53 pests were obtained from the USDA Forest Service Forest Health Technology Enterprise Team (USDA Forest Service 2021) and from various other [sources](#) (in the Tree Pest Host Data Excel file, see tab labeled "Pest Host References"). Pest range data and additional [source](#) information can be found in the iTree_Pest_Host_data file.

i-Tree Eco reports the proportion and number of live trees susceptible to each pest that is found in the study area as well as the subsequent impacts on carbon storage and sequestration, leaf area and biomass, and structural value of the potentially affected trees.

Economic Valuation

The structural value of susceptible tree species for each pest is calculated (see [Structural Valuation](#)).

Advantages, Uncertainties, and Limitations

The potential impacts of numerous insects and diseases give an indication of risk to tree species, the tree population at large, and the services trees provide. The values given are the maximum potential impact, not the actual impact, which is likely less than the potential maximum. i-Tree Eco also provides a matrix of tree species and pests showing known risks to tree species, the weighted susceptibility of a tree species to the numerous pests, and distance of the pest from the study area/county.

Table 3.—Insects and diseases evaluated by i-Tree Eco

Common Name	Scientific Name
Armillaria root disease	<i>Armillaria</i> spp.
Asian longhorned beetle	<i>Anoplophora glabripennis</i>
Aspen leafminer	<i>Phyllocnistis populiella</i>
Aspen running canker	<i>Neodothiora populina</i>
Balsam woolly adelgid	<i>Adelges piceae</i>
Beech bark disease	<i>Neonectria faginata</i>
Beech leaf disease	<i>Litylenchus crenatae mccannii</i>
Black stain root disease	<i>Leptographium wageneri</i>
Browntail moth	<i>Euproctis chrysoorrhoea</i>
Bur oak blight	<i>Tubakia iowensis</i>
Butternut canker	<i>Sirococcus clavignenti juglandacearum</i>
Chestnut blight	<i>Cryphonectria parasitica</i>
Dogwood anthracnose	<i>Discula destructiva</i>
Douglas-fir beetle	<i>Dendroctonus pseudotsugae</i>
Douglas-fir black stain root disease	<i>Leptographium wageneri</i> var. <i>pseudotsugae</i>
Dutch elm disease	<i>Ophiostoma novo-ulmi</i>
Emerald ash borer	<i>Agrilus planipennis</i>
Fir engraver	<i>Scolytus ventralis</i>
Forest tent caterpillar	<i>Malacosoma disstria</i>
Fusiform rust	<i>Cronartium quercuum</i> f. sp. <i>Fusiforme</i>
Goldspotted oak borer	<i>Agrilus auroguttatus</i>
Hemlock sawfly	<i>Neodiprion tsugae</i>
Hemlock woolly adelgid	<i>Adelges tsugae</i>
Heterobasidion root disease	<i>Heterobasidion irregulare/occidentale</i>
Jack pine budworm	<i>Choristoneura pinus</i>
Jeffrey pine beetle	<i>Dendroctonus jeffreyi</i>
Large aspen tortrix	<i>Choristoneura conflictana</i>
Laurel wilt	<i>Raffaelea lauricola</i>
Mediterranean oak borer	<i>Xyleborus monographus</i>
Mountain pine beetle	<i>Dendroctonus ponderosae</i>
Northern spruce engraver	<i>Ips perturbatus</i>
Oak wilt	<i>Bretziella fagacearum</i>
Pine black stain root disease	<i>Leptographium wageneri</i> var. <i>ponderosum</i>
Pine shoot beetle	<i>Tomicus piniperda</i>
Polyphagous shot hole borer	<i>Euwallacea</i> nov. sp.
Port-Orford-Cedar root disease	<i>Phytophthora lateralis</i>
Red pine scale	<i>Matsucoccus resinosae</i>
Sirex wood wasp	<i>Sirex noctilio</i>
Southern pine beetle	<i>Dendroctonus frontalis</i>
Spongy moth	<i>Lymantria dispar</i>
Spotted lanternfly	<i>Lycorma delicatula</i>
Spruce beetle	<i>Dendroctonus rufipennis</i>
Spruce budworm	<i>Choristoneura fumiferana</i>
Subalpine fir mortality	n/a
Sudden oak death	<i>Phytophthora ramorum</i>
Thousand canker disease	<i>Geosmithia morbida</i>
Western bark beetle	<i>Dryocoetes confusus</i>
Western blackheaded budworm	<i>Acleris gloverana</i>
Western five-needle pine mortality	n/a
Western pine beetle	<i>Dendroctonus brevicomis</i>
Western spruce budworm	<i>Choristoneura occidentalis</i>
White pine blister rust	<i>Cronartium ribicola</i>
Winter moth	<i>Operophtera brumata</i>

Planned Future Improvements

- ✿ Update species range maps and add new pests as information becomes available.

INVASIVE SPECIES

i-Tree Eco reports the total number and percentage of the tree population classified as an invasive species in the United States, as well as the associated leaf area.

Required inputs

- ✿ Tree species
- ✿ Total height
- ✿ Height to crown base
- ✿ Crown width
- ✿ Percentage canopy missing: percentage of crown volume not occupied by branches or leaves

Methods Overview

Tree species data is cross-referenced to state invasive species lists ([appendix 6](#)); for states with no data, data from the nearest state are used.

Economic Valuation

None. Research is needed on how the negative values associated with invasive species can be modeled and assessed across varying landscape types.

Advantages, Uncertainties, and Limitations

Invasiveness is dependent upon state lists; classifications vary among states.

Planned Improvements

- ✿ Add invasive species summaries; global species invasive list is being compiled by Naomi Zurcher of Arbor Aegis.

STRUCTURAL VALUATION

The structural valuation of trees is based on the trunk formula method of the Council of Tree and Landscape Appraisers (CTLA 1992). Structural value is based on the estimated cost of replacing a small tree or extending that cost to larger trees. This value is used for monetary settlement of compensation for damage or death of plants in litigation, insurance claims of direct payment, and loss of property value for tax implications.

Required Inputs

- ✿ Tree species
- ✿ D.b.h.
- ✿ Condition (% dieback)
- ✿ Land use

Methods Overview

Structural valuation is based on four tree/site characteristics: trunk area (cross-sectional area at d.b.h.), species, condition, and location. Trunk area and species are used to determine the basic value, which is then multiplied by condition (0-1) and location ratings (0-1) to determine the final tree structural value.

For transplantable trees, average replacement cost and transplantable size were obtained from International Society of Arboriculture (ISA) publications or contacting local ISA Chapters (ACRT 1997) to determine the basic replacement price (\$/cm² of cross-sectional area) for the tree. The basic replacement price from the state (or nearest state if no state data were available) is multiplied by trunk area and species factor (0-1) to determine a tree's basic value. The minimum basic value for a tree prior to species adjustment is set at \$150. Local species factors were also obtained from ISA publications ([appendix 7](#)). If no species data are available for the state, data from the nearest state are used. If no species value is found for an individual species then the average from the same genus is used. If no genus value is found, the average of results from all broadleaf or conifer equations is used.

For trees larger than transplantable size the basic value (BV) is:

$$BV = RC + (BP \times [TA_A - TA_R] \times SF)$$

Where

RC (replacement cost) = cost of a tree at the largest transplantable size,

BP (basic price) = local average cost per unit trunk area (dollars/cm²),

TA_A = trunk area (based on d.b.h.) of the tree being appraised,

TA_R = trunk area of the largest transplantable tree, and

SF = local species factor (0-1).

For trees larger than 76.2 cm in d.b.h., trunk area is adjusted downward based on the premise that a large mature tree would not increase in value as rapidly as its truck area. The following adjusted trunk-area formula is determined based on the perceived increase in tree size, expected longevity, anticipated maintenance, and structural safety (CTLA 1992):


$$ATA = -0.335d^2 + 176d - 7020$$


Where

ATA = adjusted trunk area, and

d = trunk diameter in inches (d.b.h.).

Basic value is multiplied by condition and location factors (0-1) to determine the tree's compensatory value. Percentage crown dieback is used as a proxy for tree condition where condition ratings are:

 Excellent (<1% dieback) = 1.0

 Good (1-10%) = 0.95

- ✿ Fair (11-25%) = 0.82
- ✿ Poor (26-50%) = 0.62
- ✿ Critical (51-75%) = 0.37
- ✿ Dying (76-99%) = 0.13
- ✿ Dead (100%) = 0.0

Location factors based on land use type (CTLA 1988):

- ✿ Golf course = 0.8;
- ✿ Commercial/industrial, cemetery and institutional = 0.75;
- ✿ Parks and residential = 0.6;
- ✿ Transportation = 0.5;
- ✿ Agriculture = 0.4;
- ✿ Vacant land, forested areas, and wetlands = 0.2.

More detailed methods are given in Council of Tree and Landscape Appraisers (1992) and Nowak et al. (2002a).

Non-U.S. Estimates of Structural Value

The CTLA process was also used for estimates in areas outside for the United States. However, this process required non-U.S. country specific species values and costs. In some countries, local estimates were provided by international partners, in other countries, average U.S. values were used. [Appendix 7](#) details specifics on how non-U.S. countries were addressed in estimating compensatory values.

Advantages, Uncertainties, and Limitations

The estimates of structural value are not based on CTLA's latest procedures and thus should not be used for purposes apart from i-Tree assessments. A local tree professional should be used to determine local tree values for specific cases, including potential litigation. However this adaptation of the CTLA method provides reasonable estimates of structural values based on CTLA procedures. Tree and condition factors used in the process link to i-Tree condition classes and land uses. The condition classes are not the same as identified by CTLA but are a general proxy. The land use classes used relate to older versions of the CTLA process and not the most recent guides.

Planned Improvements

- ✿ Update species and basic price values from state ISA organizations.
- ✿ Update basic price and transplantable tree prices based on producer price index.



Assessing Ecosystem Services and Values in i-Tree Eco

i-Tree Eco estimates the effects of urban forests and trees on pollution removal and human health impacts, building energy use, carbon sequestration and storage, oxygen production, ultraviolet radiation mitigation, hydrology, and wildlife suitability. To see which tree field variables are used to estimate various ecosystem services and values, see Table 2.

AIR POLLUTION REMOVAL

Air pollution removal estimates are based on modeling of gas exchange and particulate matter interception by trees, shrubs, and grass for carbon monoxide (CO), nitrogen dioxide (NO₂), ozone (O₃), particulate matter less than 10 microns (PM₁₀), particulate matter less than 2.5 microns (PM_{2.5}), and sulfur dioxide (SO₂).

Required inputs

-  Tree, shrub, and grass cover
-  Tree species

Methods Overview

i-Tree Eco estimates the hourly dry deposition of O₃, SO₂, NO₂, CO, PM₁₀ and PM_{2.5} throughout the year based on tree, shrub and grass cover data, hourly National Climatic Data Center (Lindsey 2022) weather data and U.S. Environmental Protection Agency (U.S. EPA) pollution-concentration monitoring data. Missing hourly pollution data are filled in based on procedures detailed in Hirabayashi and Endreny (2016). Weather station data quality information is detailed in Hirabayashi (2017). Daily particulate matter data are used as hourly inputs (i.e., daily average is used for each hour of the corresponding day). If multiple monitors exist, the average of all monitor data are used. Missing hourly pollution data are filled in based on procedures detailed in Hirabayashi and Kroll (2017).

Pollution removal, or downward pollutant flux (F; in g/m²/s), is calculated as:

$$F = V_d C$$

Where

V_d = deposition velocity (m/s), and

C = pollutant concentration (g/m³)

Deposition velocity is calculated as (Baldocchi et al. 1987):

$$V_d = 1/(R_a + R_b + R_c)$$

Where

R_a = sum of the aerodynamic boundary layer,

R_b = quasi-laminar boundary layer, and

(R_c) = canopy resistances.

Hourly estimates of R_a and R_b are calculated using standard resistance formulas (Killus et al. 1984, Nowak et al. 1998, Pederson et al. 1995) and hourly weather data. R_a and R_b effects are relatively small compared to R_c effects.

Hourly canopy resistance values for O₃, SO₂, and NO₂ are calculated based on a modified hybrid of big-leaf and multilayer canopy deposition models (Baldocchi 1988, Baldocchi et al. 1987). Canopy resistance (R_c) has three components: stomatal resistance (r_s), mesophyll resistance (r_m), and cuticular resistance (r_t), such that:

$$1/R_c = 1/(r_s+r_m)+1/r_t$$

Mesophyll resistance is set to 0 seconds/meter (s/m) for SO₂ (Wesely 1989) and 10 s/m for O₃ (Hosker and Lindberg 1982). Mesophyll resistance is set to 100 s/m for NO₂ to account for the difference between transport of water and NO₂ in the leaf interior and to bring the computed deposition velocities in the range typically exhibited for NO₂ (Lovett 1994). Base cuticular resistances are set at 8,000 s/m for SO₂, 10,000 s/m for O₃, and 20,000 s/m for NO₂ to account for the typical variation in r_t exhibited among the pollutants (Lovett 1994).

Hourly inputs to calculate canopy resistance are photosynthetic active radiation (PAR; μE/m²/s), air temperature (K °), windspeed (m/s), frictional velocity (u_{*}) (m/s), CO₂ concentration (set to 390 ppm), and absolute humidity (kg/m³). Air temperature, windspeed, u_{*}, and absolute humidity are measured directly or calculated from measured hourly NCDC meteorological data. Total solar radiation is calculated based on the meteorological/statistical (METSTAT) model with inputs from NCDC data (Maxwell 1994). PAR is calculated as 46 percent of total solar radiation input (Monteith and Unsworth 1990).

As removal of CO and particulate matter by vegetation is not directly related to transpiration, R_c for CO is set to a constant for in-leaf season (50,000 s/m) and leaf-off season (1,000,000 s/m) based on data from Bidwell and Fraser (1972). For PM₁₀, the median deposition velocity from the literature (Lovett 1994) is 0.0128 m/s for the in-leaf season. Base particle V_d is set to 0.064 based on a LAI of 6 and a 50 percent resuspension rate of particles back to the atmosphere (Zinke 1967). The base V_d is adjusted according to actual LAI and in-leaf vs. leaf-off season parameters. For PM_{2.5}, hourly deposition velocities and resuspension rates vary with wind speed as detailed in Nowak et al. (2013b).

To limit deposition estimates to periods of dry deposition, deposition velocities are set to 0 during periods of precipitation. The model is run at the population scale to estimate pollution effects. Average hourly pollutant flux (g/m² of tree canopy coverage) among the pollutant monitor sites is multiplied by total tree-canopy coverage (m²) to estimate total hourly pollutant removal by trees across the study area.

Daily leaf area is determined based on:

- ✦ Percentage evergreen tree species.
- ✦ Leaf-on / leaf-off dates – based on first and last frost dates from Lindsey 2022 for the United States and Weather Online (2016) for international locations.
- ✦ Daily LAI – maximum LAI is derived from field data. Daily estimates combined LAI values with percentage evergreen information and local leaf-on and leaf-off to estimate total daily leaf surface area assuming a 4-week transition period centered on leaf-on and leaf-off dates for spring and autumn, respectively. Detailed methods are given in Hirabayashi and Nowak (2016).

Limits of total tree removal of O₃, NO₂, SO₂, and PM₁₀ are estimated using the typical range of published in-leaf dry deposition velocities (Lovett 1994). The ability of individual trees to remove pollutants is estimated for each diameter class using the formula (Nowak 1994a):

$$I_x = R_t \times (LA_x / LA_t)$$

Where

I_x = pollution removal by individual tree x (kg),

R_t = total pollution removed for all trees (kg),

LA_x = total leaf area of tree x (m²), and

LA_t = total leaf area of all trees (m²).

This formula yields an estimate of pollution removal by individual trees based on leaf surface area (LA), the major surface for pollutant removal.

To estimate percentage air quality improvement due to the removal of dry deposition (Nowak et al. 2000), mixing height data⁷ from closest radiosonde station (from [NOAA's Earth System Research Laboratory](#)) are used in conjunction with local deposition velocities. Daily morning and afternoon mixing heights from the closest station is interpolated to produce hourly values using the U.S. EPA's PCRAMMIT program (U.S. EPA 1999). Minimum boundary-layer heights are set to 150 m during the night and 250 m during the day based on estimated minimum boundary-layer heights in cities. Hourly mixing heights (in meters) are used in conjunction with pollution concentrations (µg/m³) to calculate the amount of pollution within the mixing layer (µg/m²). This extrapolation from ground-layer concentration to total pollution within the boundary layer assumes a well-mixed boundary layer, which is common in daytime (unstable conditions) (Colbeck and Harrison 1985). Hourly change in pollution concentration is calculated as:

$$\Delta C = \Delta P_t / (BL \times CA)$$

Where

ΔC = change in concentration (µg/m³),

ΔP_t = change in pollutant mass (µg) due to the net of effect of removal (flux),

BL = boundary layer height (m), and

CA = study area (m²).

Percentage air quality improvement is calculated as:

$$\% \Delta = \Delta P_t / (\Delta P_t + P_a)$$

Where

P_a = pollutant mass in the atmosphere (µg), which equals measured concentration (µg/m³) × BL × CA .

⁷ Mixing height is a height in the lower atmosphere that, below this height, undergoes mechanical or turbulent mixing, producing a nearly homogeneous air mass.

Health benefits, and the associated economic value of these benefits, from the removal of pollutants NO₂, SO₂, O₃, and PM_{2.5}, are made based on the U.S. EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) model (U.S. EPA 2012) with methods detailed in Nowak et al. (2013a, 2014). Based on BenMAP, various standardized health impacts and dollar values were calculated for each U.S. county. The standardized values were calculated for each pollutant as the impact or value/person/pollutant concentration change using local pollution and population data. These values are multiplied by the corresponding local population total with a county from U.S. Census data and pollution concentration change due to trees and other vegetation in the study area to determine health impacts and associated dollar values. More detailed documentation and formulas are given in Hirabayashi et al. (2015) and Hirabayashi (2016).

Economic Valuation

Economic valuation of pollution removal is estimated in one of two ways:

- 1) Externality values. These values can be considered the estimated cost of pollution to society that is not accounted for in the market price of the goods or services that produced the pollution. i-Tree Eco uses estimates of externality values (Murray et al. 1994, Ottinger et al. 1990) for the valuation of CO (\$1,599/tonne⁸ in 2011 dollars); these values are updated based on the producer price index (U.S. Bureau of Labor Statistics 2017).
- 2) Health values. i-Tree estimates the number of incidents avoided and the total dollar value of several health factors related to four other pollutants: NO₂, SO₂, O₃, and PM_{2.5}. The estimates are based on health-care expenses (i.e., cost of illness), productivity losses associated with specific adverse health events, and on the value of a statistical life in the case of mortality as derived from the U.S. EPA BenMAP model (Nowak et al. 2014, U.S. EPA 2012)

For international estimates, regression equations (Nowak et al. 2014) based on population density can be used to estimate a dollar value per ton of pollution removal.

Advantages, Uncertainties, and Limitations

The i-Tree model produces deposition velocities and daily flux patterns that coincide with measured field data (e.g., Lovett 1994, Morani et al. 2014). The hourly routines allow for interactions between pollution concentrations and deposition velocities to be quantified, which are missed using annual, monthly, or daily average data. Sensitivity analyses of dry deposition velocity reveals that estimates of these velocities are most sensitive to the inputs of air temperature and leaf area index (Hirabayashi et al. 2011).

Pollution removal is modeled based on hourly measured pollution concentrations. The concentrations often come from only one local monitor, or the average of several monitors. Thus only one concentration value per hour is used to represent the entire study area. This approach has limited spatial resolution of concentration data in the study area, which is necessitated by limited spatially specific pollution concentration data. If more spatially refined pollution data exist, the model can run multiple times using various zones within the city with different pollution concentration data.

⁸ Tonne is a metric measure and is equal to 1,000 kg. The North American ton (only used in the United States and Canada) is equal to 2,000 pounds or 907.1847 kg

Health impacts are dependent on the estimations based on the U.S. EPA BenMAP model, which utilizes epidemiological data to estimate health impacts due to changes in pollution concentrations. Coupling BenMAP with i-Tree estimates of air pollution removal by trees is the only known program that estimates health benefits of trees' ecosystem service of pollution removal. Health estimates can be estimated for any area in which local population data by age class and tree cover data exists. These health-benefit estimates would be locally specific, except for pollution concentration data, which may be developed from a larger geographic area (i.e., concentration data are necessarily specific to each local geography).

This process accurately estimates pollution removal. However, it only estimates pollution removal and the removal effect on local pollutant concentrations; it does not account for tree impacts regarding:

- ✿ Local scale interactions with wind. Trees alter wind patterns that can either increase or decrease concentrations at the local site scale.
- ✿ Potential pollution formation due to volatile organic compounds emissions.
- ✿ Potential health impacts due to tree pollen.
- ✿ Drought. i-Tree Eco assumes ample soil moisture so that gas exchange can occur. During drought, the module will overestimate pollution removal of NO₂, SO₂, and O₃. However, even if drought effects are modeled, the important question in urban areas is to know when the trees actually have drought effects. Even though a natural forest may experience drought, urban trees often do not have drought effects due to watering of trees by humans and possible leaky pipes that supplement natural soil moisture.

Estimates of interception and resuspension of PM_{2.5} are based on local leaf area, wind-speed, precipitation, and pollution concentrations (Nowak et al. 2013b). Estimates of removal of PM₁₀ and CO are rather rudimentary and based on average deposition velocities or, in the case of CO, very limited research. More research is needed regarding tree impacts on PM_{2.5}, PM₁₀, and CO concentrations so that estimates can be improved. In addition, more spatially refined pollution concentration data would aid in assessing more locally specific tree effects.

Planned Improvements

- ✿ Add new weather and pollution data years as they become available.
- ✿ Develop and add a drought routine to account for the limited gas exchange during droughts.
- ✿ Undertake xylem conduit analyses to help separate species differences in gas exchange to help determine differences in pollution removal among tree species.
- ✿ Add new externality values (Korzhenevych et al. 2014, van Essen et al. 2011) as an option for economic valuation.
- ✿ Update economic values to most recent dollar year.
- ✿ Give users the option of selecting which pollution monitor station to use in their project.

ALLERGENICITY INDEX

This index rates the allergenicity of the urban forest based on methods detailed in Nowak and Ogren (2021).

Planned Improvements

- ✿ Adding estimates of total pollen loads by species.

BUILDING ENERGY USE AND EMISSIONS

i-Tree Eco estimates the effects of trees on energy consumption and pollutant emissions from residential buildings. The effects are broken down by building energy use and energy influence type.

Required Inputs

- ✿ Species
- ✿ Tree height
- ✿ Percentage canopy missing: percent of crown volume not occupied by branches or leaves
- ✿ Crown dieback: percentage crown dieback in live crown area
- ✿ Direction to building
- ✿ Shortest distance to the building

Methods Overview

Methods for energy estimates are based on McPherson and Simpson (1999). For each tree within 18 m of a one- or two-story residential building, information on distance and direction to the building is recorded. Any tree that is less than 6 m in height or farther than 18 m from a building is considered to have no effect on building energy use.

Using the tree size, distance, direction to building, climate region, leaf type (deciduous or evergreen), and percentage cover of buildings and trees on the plot, the amount of carbon avoided from power plants due to the presence of trees is estimated based on methods in McPherson and Simpson (1999). The amount of carbon avoided is categorized into megawatt-hour (MWh; for cooling) and million British thermal units (MMBtus) and MWh (for heating) altered due to tree effects. Default energy effects per tree are set for each climate region, vintage building types (period of construction), tree size class, distance from building, energy use (heating or cooling), and/or leaf type (deciduous or evergreen) depending upon the energy effect of the tree (tree shade, windbreak effects, and local climate effect) (McPherson and Simpson 1999). Default shading and climate effect values are applied to all trees; estimates of altered heating due to windbreaks are assigned to each evergreen tree. As shading effect default values are only given for one vintage building type (post-1980), vintage adjustment factors (McPherson and Simpson 1999) are applied to obtain shading effect values for all other types.

i-Tree adjust for varying energy effects due to poor tree condition. The default energy effect values are adjusted as follows:

$$\text{Energy adjustment} = 0.5 + (0.5 \times \text{tree condition})$$

Where

Tree condition = 1 - percentage dieback.

This adjustment factor is applied to all tree energy effects for cooling, but only evergreen trees for the effects for heating.

As tree cover increases in an area, the individual tree effect on climate diminishes, though the cumulative effect of all trees can increase. Base climate effect values for a tree are given for plots of 10, 30 and 60 percent cover (McPherson and Simpson 1999) and interpolation formulas are used to determine the actual tree value based on the percentage of tree and building cover on a specific plot. For plots with less than 10 percent cover, the slope between the 10 and 30 percent cover values is used for the interpolation. Plots with percent cover greater than 60 percent used the slope between 30 and 60 percent cover with a minimum individual tree climate effect of one-third the effect at 60 percent cover. This minimum is set to prevent a tree from obtaining a zero or negative effect at high cover (100 percent).

The total shading, windbreak, and climate energy effects due to trees on a plot are calculated by summing the individual tree's energy effects for the particular energy use and housing vintage. These values are adjusted for the distribution of the different vintage types within the climate region (McPherson and Simpson 1999).

Energy use effects are converted to pollutant emissions avoided using State estimates of pollutant emissions from power plants per MWh or MMBtu produced. Pollutant emissions are estimated for CO₂, NO_x, SO₂, CO, methane (CH₄), volatile organic compounds (VOCs), and PM₁₀ and PM_{2.5}.

These estimates are based on the U.S. EPA Emissions and Generation Resource Integrated Database (eGRID) (Cai et al. 2012, Deru and Torcellini 2007, U.S. EPA 2013), which provides environmental characteristics of almost all electrical power generated in the United States. MMBtu conversion factors (tonnes of pollutants/MMbtu) are based on fuel type (e.g., natural gas, fuel oil, wood). State MMBtu's conversion factors are used for CO₂, NO_x, and SO₂ based on eGRID data (Deru and Torcellini 2007, U.S. EPA 2013). For CO, CH₄, VOCs, and PM₁₀, national average conversion factors are applied (Leonardo Academy 2011). For PM_{2.5}, no value was found for MMBtus so the ratio of MWh emissions between PM_{2.5} and PM₁₀ is applied to PM₁₀ MMBtu emissions to estimate PM_{2.5} from MMBtu. Pollutant emissions by fuel type are weighted by state average fuel use for heating (McPherson and Simpson 1999) to estimate total emissions associated with changes in energy use. Plot effects are combined to yield the total energy and associated emissions effects due to the urban forest.

Economic Valuation

The cost of electricity (\$/kWh) is based on 2020 state average energy values (U.S. Energy Information Administration 2019a). The 2020 cost of fuels (\$/MMBtu) is a combination of average state costs for natural gas, fuel oil, and wood (U.S. Energy Information Administration 2019b, c, d) ([appendix 8](#)). Average price for change in energy use due to trees are based on state average distribution of buildings that heat by natural gas, fuel oil, and other (including wood) (McPherson and Simpson 1999).

Various approaches are used to estimate the values of the changes in emissions. The CO₂ value varies through time based on year and adjustments to the dollar value based on the producer price index. The current CO₂ value is estimated at \$51.23 per tonne based on the estimated social costs of carbon for 2020 with a 3 percent discount rate updated to 2018 dollars (Interagency Working Group 2016). The CH₄ value is estimated at \$980 per tonne based on the ratio of the estimated social costs of methane to carbon dioxide (ratio =24.5) for 2010 with a 3 percent discount rate (Marten and Newbold 2011). This ratio is

applied to the most recent CO₂ value to update the value for CH₄. Social costs estimate the monetized damages associated with incremental increases in emissions and include changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change (Interagency Working Group 2016).

Pollution removal value for CO is estimated using national median externality values (\$1,599/tonne in 2011 dollars) (Murray et al. 1994). Externality values can be considered the estimated cost of pollution to society that is not accounted for in the market price of the goods or services that produced the pollution.

Median air pollution cost factors from Europe (2008), which are similar to externality values and include health costs, building and material damage, and crop losses (van Essen et al. 2011), are used to estimate the values of NO_x (\$9,411/tonne), SO₂ (\$8,929/tonne), VOCs (\$1,207/tonne), PM₁₀ (\$56,346/tonne), and PM_{2.5} (\$140,926/tonne). These values are updated based on the producer price index (U.S. Bureau of Labor Statistics 2017). As of November 2021, the amounts and values of CH₄ have yet to be incorporated into i-Tree Eco and other programs (e.g., i-Tree Design, MyTree).

Non-U.S. Estimates of Building Energy Effects

The i-Tree process for estimating tree effects on building energy use were developed for U.S. climate, buildings, and fuel use. Using this procedure outside the United States has significant limitations. However, numerous users insist on some type of estimation of energy impacts from i-Tree outside the United States. Thus, the i-Tree model has been applied in other countries, but with the following warning:

Because this model component is designed specifically for the U.S., its utility is limited in international applications. International users will receive energy results that are based on the characteristics of the user-defined U.S. climate region, including emission factors, typical construction practices and building characteristics, and energy composition (i.e., type of and amount used). Therefore, results should be used with caution as they assume that the building types, energy use, and emission factors of the U.S. are the same as those internationally (i-Tree 2019b).

The only local values used in the estimates outside the United States are electricity and fuel costs. The remainder of the estimation is based U.S. conditions from the assigned climate zone. Details on local energy values and the comparisons between international areas and U.S. climate zones is given in [appendix 9](#).

Advantages, Uncertainties, and Limitations

i-Tree Eco uses results from building energy simulations from numerous climates across the United States with tree results varying based on tree size and position around the building. i-Tree Eco relies on state-specific energy and emission values. However, it is unknown how well these values represent actual energy savings, so it is difficult to validate tree effects on energy use, leading to uncertainties. The results are likely reasonable as the model simulations appear reasonable, but the uncertainty of the estimates is unknown.

Planned Improvements

- ✿ Add emission amounts and values for CH₄, CO, NO_x, SO₂, VOCs, PM₁₀, and PM_{2.5}.
- ✿ Work with SUNY College of Environmental Science and Forestry to develop a new, more robust energy program.
- ✿ Add local health values based on county-based BenMAP values.

CARBON STORAGE AND SEQUESTRATION

Carbon dioxide (CO₂) in the atmosphere is necessary for plants and trees to grow. Trees absorb carbon dioxide during photosynthesis, storing carbon and producing oxygen as a byproduct of photosynthesis. Carbon sequestration is the process of removing carbon from the atmosphere and storing it in a physical element (e.g., a tree). i-Tree Eco estimates carbon storage in trees, annual carbon sequestration, and emission of carbon via tree decomposition.

Required inputs

- ✿ Tree species
- ✿ D.b.h.
- ✿ Total tree height
- ✿ Crown dieback
- ✿ Crown light exposure

Methods Overview

Carbon storage is estimated by multiplying tree biomass by 0.5 (Chow and Rolfe 1989) or 0.41 for palm trees (Sanquetta et al. 2015). To prevent carbon storage overestimation for very large trees, total carbon sequestration is limited to a maximum of 40 kg C / cm d.b.h. growth once a tree reaches 7,500 kg of carbon in i-Tree Eco and Forecast. To estimate annual gross carbon sequestration, the tree d.b.h. is incrementally increased in the computer model based on an estimated annual growth rate. The carbon storage in the current year (year 0) is then contrasted with carbon storage in the next year (year 1) to estimate the annual sequestration. If a tree's carbon storage is over 7,500 kg and the tree is alive, carbon sequestration for these large trees is estimated based on the sequestration rate (kg/cm d.b.h. growth) when the tree reached 7,500 kg C storage. A maximum sequestration rate was set at 40 kg/cm d.b.h. growth if the tree's storage was greater than 7,500 kg. These sequestration values are added to the storage value annually, so storage can exceed 7500 kg, but the sequestration rates are prevented from growing geometrically based on carbon equations applied to large trees. Tropical biomass equations from wet, moist, and dry tropical forests (Chave et al. 2005) are used in tropical areas (Figure 13) instead of current biomass equations. However, users can opt to not use these tropical equations and use standard i-Tree carbon equations

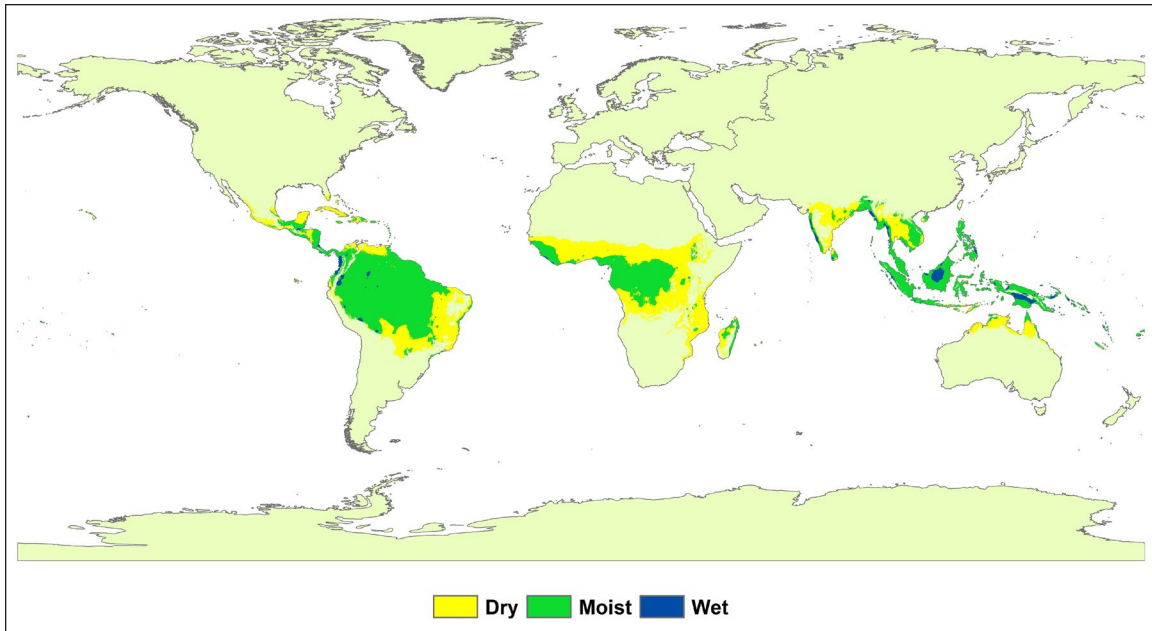


Figure 13.—Locations where tropical equations are used.

Tree Growth

Annual tree diameter growth is estimated for the study area based on:

1. Base growth rate—Open grown tree growth rates were based on measured street tree growth (Fleming 1988, Frelich 1992, Nowak 1994b), which were standardized to a 153 day frost free length as follows:

$$\text{standard growth} = \text{measured growth} \times \left(\frac{153}{\text{number of frost-free days of measurement}} \right).$$

The average diameter growth rate for open-grown trees with 153 frost free days is 0.84 cm/yr.

2. Length of growing season—To determine a local base growth rate, the standard growth rate was adjusted based the local length of growing as follows:

$$\text{base growth} = \text{standard growth} \times \left(\frac{\text{number of frost-free days in area}}{153} \right).$$

3. Species growth rates—Based on these data, the average standardized diameter growth rates for open-grown trees with 153 frost free days are set to 0.58 cm/yr for slow growing species, 0.84 cm/yr for moderate growing species, and 1.09 cm/yr for fast growing species (species information can be seen and input via i-Tree Database, (<https://database.itreetools.org/#/splash>)). There are limited measured data on urban tree growth for slow, moderate, or fast-growing tree species, so the growth rates used in i-Tree Forecast are estimates.

4. Tree competition—Crown light exposure (CLE) measurements are used to represent tree competition. CLE measurements for each tree are based on the number of sides and/or top of tree exposed to sunlight. A CLE of 0-1 represents forest conditions with a closed, or nearly closed canopy, where none or one side of the tree is exposed to sunlight. CLE of 2-3 represents park conditions and 4-5 represents open-grown conditions. Based on a

comparison of species growth rates between street trees (CLE 4-5), park trees (CLE 2-3) and forest-grown trees (CLE 0-1) (deVries 1987, Fleming 1988, Frelich 1992, Nowak 1994b, Smith and Shifley 1984), the base growth for trees are as follows:

trees with CLE 0-1 = Standardized growth (SG) \times 0.44;

trees with CLE 2-3 = SG \times 0.56, and

trees with CLE 4-5 = SG \times 1.

5. Tree condition—Growth rates are adjusted for tree condition based on percentage crown dieback. Base growth rates are multiplied by 1 – percentage dieback. For example, a tree with 40 percent dieback, base growth rates are multiplied by 0.6.

6. Maximum d.b.h.—As a tree approaches “maximum” d.b.h., growth rate decreases. Thus, the species growth rates as described above are adjusted based on the ratio between the current d.b.h. of the tree and the maximum d.b.h. for the species. The estimated tree height at maturity is derived from the literature. If height at maturity is less than 12.2 m, maximum d.b.h. is set at 38.1 cm; for height at maturity between 12.2 m and 18.3 m, maximum d.b.h. is set at 76.2 cm; for height at maturity >18.3 m, maximum d.b.h. is set at 114.3 cm. When a tree’s d.b.h. is more than 80 percent of its maximum d.b.h., the annual diameter growth is proportionally reduced from full growth at 80 percent of maximum d.b.h. to 2.22 percent of full growth at 125 percent of maximum d.b.h.

Decomposition

An estimation of the carbon lost due to more rapid carbon release (e.g., mulching of tree components and burning) and delayed release (e.g., decomposition) is calculated and subtracted from the gross sequestration to estimate net sequestration. To estimate carbon release, various assumptions are made related to probability of mortality, probability of recording a dead tree, and decomposition rates. More detailed information on storage, gross and net sequestration, and tree growth can be found in Nowak et al. 2002b, 2008.

Economic Valuation

The value of carbon storage and sequestration is based on the social cost of carbon as reported by the Interagency Working Group on Social Cost of Carbon (2016). Social cost associated with a pollutant (e.g., CO₂) refers to an estimate of total (global) economic damage attributable to incremental increase in the level of that particular pollutant in a given year. The current CO₂ value is estimated at \$51.23 per tonne based on the estimated social costs of carbon for 2020 with a 3 percent discount rate to reflect 2018 dollars (Interagency Working Group 2016). Users can adjust this value, if they so desire, by taking a ratio of the desired value (DR) per tonne CO₂ to the \$51.23/tonne CO₂ (updated value = i-Tree reported value \times DR/51.23).

Advantages, Uncertainties, and Limitations

The advantages and limitations associated with carbon storage estimates are the same as with tree biomass estimates (provided earlier) as carbon storage is directly related to biomass. Overall the storage estimates are reasonable and the standardized values per unit tree cover are comparable to estimates for U.S. forests and from other cities around the world (Nowak et al. 2013a). National estimates of urban forest carbon storage and sequestration have been estimated through the years using this procedure (Nowak 1993,

Nowak and Crane 2002, Nowak et al. 2013a). Estimates of storage could be improved with biomass equations developed for urban conditions. Capping carbon sequestration after the tree reaches 7,500 kg is also a limitation, however, the cap prevents extremely large estimates from occurring via the logarithmic biomass equations used.

Estimates of gross carbon sequestration are dependent upon good biomass and tree growth equations. Growth rates for urban trees will range between 0 cm d.b.h./yr (dead trees) to 2.54 cm d.b.h./yr for fast-growing, open-grown healthy trees in areas with no frost. Estimated growth rates are average rates where rates of individual trees may be higher or lower than the estimated class average. These growth rates for “moderate” trees are within range for measured urban and forest tree growth (e.g., deVries 1987, Fleming 1988, Frelich 1992, Nowak 1994b, Smith and Shifley 1984, Wood 2010).

For i-Tree programs that simulate long-term tree growth and carbon sequestration (i.e., i-Tree Forecast, Planting, Design), growth rate estimates can have a substantial impact on carbon sequestered. The estimated growth is based on the tree species, condition, and crown light exposure of the measured tree. Better long-term growth rates for trees will help improve growth estimates.

Net sequestration is based on gross sequestration minus losses due to decomposition. Decomposition estimates are quite rudimentary and are based on various assumptions of mortality and decomposition rates. Improved research on decomposition rates, how wood is decomposed (e.g., burn, mulch, natural decomposition), and mortality rates for urban trees are needed to enhance the net sequestration estimates.

Planned Improvements

- ✿ Potential wood products derived from removed trees is also being incorporated in i-Tree Eco (Nowak et al. 2019).
- ✿ Integration of FIA national scale volume and biomass equations.

FOOD PROVISIONING SERVICES

Individual species characteristics about fruit, flowers, pollinators, and potential use for pharmaceuticals, fiber, food and fuel are provided for 44 tree species if these species are found within the local assessment. This information is provided to communicate the value of various species and aid in appropriate species selections. These data were gathered by the Community Food Forestry Initiative (Inhabit.earth, n.d.).

Planned Improvements

- ✿ Add information for more tree species.
- ✿ Add species pollen production estimates.

LEAF NUTRIENTS

This module estimates the amount and value of leaf nutrients (carbon, nitrogen, potassium, phosphorus, calcium, manganese, and magnesium) contained in deciduous leaves (annual leaf drop) based on methods detailed in Nowak et al. (2019).

Planned Improvements

- ✿ None.

OXYGEN PRODUCTION

As trees capture carbon dioxide during the photosynthesis process, they give off oxygen. Likewise, when carbon dioxide is released through decomposition, oxygen is consumed. The oxygen production estimates directly relate to estimates of carbon sequestration.

Required Inputs

Same as for [Carbon Storage and Sequestration](#):

- ✿ Tree species
- ✿ D.b.h.
- ✿ Total tree height
- ✿ Crown dieback

Methods Overview

The amount of oxygen produced is estimated from carbon sequestration based on atomic weights:

$$\text{net } O_2 \text{ release (kg/yr)} = \text{net } C \text{ sequestration (kg/yr)} \times 32/12$$

More detailed methods are given in Nowak et al. (2007b).

Economic Valuation

i-Tree assigns the value of oxygen production at \$0/tonne. The reason the oxygen production value of trees is insignificant is due to the large amount of oxygen within the atmosphere (approximately 21 percent of the atmosphere's volume is oxygen) and because species of algae are estimated to replace about 90 percent of all oxygen used. Thus, though trees do produce significant amounts of oxygen, it is not a significant ecological benefit (see Nowak et al. 2007b).

Advantages, Uncertainties, and Limitations

Same as for [Carbon Storage and Sequestration](#).

Planned Improvements

- ✿ None.

STREAM FLOW AND WATER QUALITY

i-Tree Eco estimates the amount of rainfall intercepted, stored, transpired, and evaporated by urban forest tree canopies as well as the volume of runoff avoided due to trees' presence.

Required Inputs

- ✿ Species
- ✿ Total height
- ✿ Height to crown base
- ✿ Crown width

- ✿ Percentage canopy missing: percentage of crown volume not occupied by branches or leaves
- ✿ Total tree cover

Methods Overview

Based on leaf/bark area data and local hourly weather data, i-Tree Eco estimates hourly rain interception, evaporation from leaf surfaces, potential evapotranspiration, transpiration, and avoided runoff values. These calculations are process-based, meaning each process is simulated individually and then linked with other processes. For example, interception is simulated using an improved Rutter methodology (Valente et al. 1997), and evaporation is simulated based on the work of Deardorff (1978) and Noilhan and Planton (1989). Estimates are generated based on current tree conditions and then without trees in order to estimate the impact of trees on surface runoff. Impervious cover beneath trees is assumed to be 25.5 percent, the national average impervious cover (Nowak and Greenfield 2012). To estimate individual tree effects, the water impacts across the entire population of trees are prorated back to the tree-scale proportional to tree leaf area of the individual tree.

There are numerous calculations made to estimate hourly interception, evaporation, transpiration, potential evapotranspiration, and avoided runoff values. These equations and methods are detailed in Hirabayashi et al. (2015), Hirabayashi (2013, 2016), Wang et al. (2008), and Yang et al. (2011).

Economic Valuation

i-Tree Eco uses the U.S. national average dollar value of \$0.008936/gallon to estimate the value avoided runoff due to trees. The value is based on 16 research studies on costs of storm water control and treatment (McPherson et al. 1999, 2000, 2001, 2002, 2003, 2004, 2006a, 2006b, 2006c, 2007, 2010; Peper et al. 2009, 2010; Vargas et al. 2007a, 2007b, 2008). Interestingly, the median sale price charged in competitive water markets for municipal uses was \$2,120 per million liters (Binder et al. 2017), which converts to \$0.008025 per gallon (90% of i-Tree value).

Advantages, Uncertainties, and Limitations

i-Tree Eco offers fast and easy access to robust, process-based hydrology estimates. Hydrologic models that are easier to use often do not have robust, process-based estimates, while models with more robust methods tend to require more technical expertise. Few hydrologic models explicitly simulate eco-hydrology of trees (Coville et al. 2020).

While this is one of the easiest-to-use tree-based simulations of hydrology, it has limitations: it simplifies surface and subsurface hydrology to focus on the effects of trees. i-Tree Hydro provides more comprehensive processing of hydrologic effects than i-Tree Eco. Eco's subsurface routines are simplified and do not take into account varying amounts of impervious cover. Both i-Tree Eco and i-Tree Hydro do not account for the effects of different spatial arrangements of trees or other land cover. They are statistically rather than spatially distributed rainfall-runoff models, accounting for the amount of tree cover relative to other land cover types.

i-Tree Eco also uses default soil and hydrologic parameters (e.g., soil texture class) for the nation. This is suitable for first-order comparisons between different land cover amounts

in any given area, but it comes with uncertainty about how well those defaults describe local conditions in various areas.

Economic valuation of reduced runoff is also a limitation with i-Tree Eco as it uses an estimated average storm water control cost, which is a very rough approximation of value. Approaches and estimates of the economic valuation of change in stream water flow and quality are limited. As better estimates become available, they will be used. Users can also use local values, if known, by using a ratio of the local value to the model default value (\$0.008936/gallon runoff).

Planned Future Improvements

- ✿ Add water quality effects of trees based on runoff volume and local watershed event mean concentration (EMC) values.
- ✿ Update economic values to most recent dollar year.

VOLATILE ORGANIC COMPOUND EMISSIONS

Volatile organic compounds (VOCs) are emitted by trees and are precursor chemicals to ozone and other pollutant formation. Thus, VOC emissions can be considered a disservice via the potential formation of ozone and other pollutants. Species have varying emission rates based on leaf biomass and local meteorological conditions.

Required Inputs

- ✿ Species
- ✿ Total height
- ✿ Height to crown base
- ✿ Crown width
- ✿ Percentage canopy missing: percentage of crown volume not occupied by branches or leaves

Methods Overview

Tree VOC emissions are computed based on procedures used in the EPA's Biogenic Emissions Inventory System (BEIS) (U.S. EPA 2017a). The VOC emissions depend on tree species, leaf biomass, air temperature, and other environmental factors. i-Tree Eco estimates the hourly emission of isoprene (C₅H₈) and monoterpenes (C₁₀ terpenoids), the two dominant VOC categories emitted by trees. Leaf biomass estimates are derived from the field data and multiplied by genus- or family-specific emission factors (Nowak et al. 2002b) to produce emission levels standardized to 30 °C and photosynthetically active radiation (PAR) flux of 1,000 μmol/m²/s. The genus- or family-specific emission factors were derived from the literature ([appendix 12](#)). If genus-specific information is not available, median emission values for the family, order, or superorder are used. Standardized emissions are converted to actual emissions based on light and temperature correction factors (Geron et al. 1994) and local meteorological data.

VOC emission (E) in μgC/tree/hr for isoprene and monoterpenes is estimated as:

$$E = B_E \times B \times \gamma$$

Where

B_E is the base genus emission rate in $\mu\text{gC/g}$ leaf dry weight/hr at 30 °C and PAR flux of 1,000 $\mu\text{mol/m}^2/\text{s}$,

B is species leaf dry weight biomass (g), and

for isoprene emission is calculated as:

$$\gamma = [\alpha \cdot c_{L1} L / (1 + \alpha^2 \cdot L^2)^{\frac{1}{2}}] \cdot [\exp[c_{T1}(T - T_S) / R \cdot T_S \cdot T] / (0.961 + \exp[c_{T2}(T - T_M) / R \cdot T_S \cdot T])]$$

Where

$\alpha = 0.0027$,

$c_{L1} = 1.066$,

L is PAR flux,

R is the ideal gas constant (8.314 J/K/mol),

T (°K) is leaf temperature, which is assumed to be air temperature,

T_S is standard temperature (303 °K),

$T_M = 314$ °K,

$C_{T1} = 95,000$ J/mol, and

$C_{T2} = 230,000$ J/mol (Geron et al. 1994, Guenther 1997, Guenther et al. 1995).

As PAR strongly controls the isoprene emission rate, PAR is estimated at 30 canopy levels as a function of above-canopy PAR using the sunfleck canopy environment model⁹ with the LAI derived from the field measurements.

For monoterpenes:

$$\gamma = \exp[\beta(T - T_S)]$$

Where

T (°K) is leaf temperature, which is assumed to be air temperature,

$T_S = 303$ °K, and

$\beta = 0.09$.

Hourly inputs of air temperature are from measured National Climatic Data Center (NCDC) meteorological data. Total solar radiation is calculated based on the National Renewable Energy Laboratory Meteorological/Statistical Solar Radiation Model (METSTAT) with inputs from the NCDC data set (Maxwell 1994). PAR is calculated as 46 percent of total solar radiation input (Monteith and Unsworth 1990). Hourly VOC estimates are summed to produce a VOC emission rate per genera. To estimate individual tree VOC emissions, the total genera emission is prorated back to the tree or species level proportional to individual tree or species biomass in the genera. More detail methods are given in Hirabayashi (2012, 2016).

⁹ A. Guenther, National Center for Atmospheric Research, pers. commun., 1998

Economic Valuation

Not assessed; VOC emissions need to be converted to ozone impacts prior to being valued.

Advantages, Uncertainties, and Limitations

The VOC emission values produced by i-Tree Eco are closely aligned with standardized values produced by U.S. land use inventory (Kinnee et al. 1997). The modeled pattern of photosynthetically active radiation (PAR) also closely matches measures of PAR radiation. However, this module only estimates VOC emissions and does estimate ozone formation from VOC emissions to contrast against ozone removal by trees. Photochemical models are likely the best means to determine the ultimate effects of VOC emissions on ozone formation.

Planned Improvements

- ✿ Add simplified means of converting VOC emissions to ozone formation.

ULTRAVIOLET RADIATION

i-Tree Eco quantifies urban tree effects on mitigating the intensity of ultraviolet (UV) radiation on the ground within different land use types across a study area. The ultraviolet index or UV index is an international standard measurement of the strength of sunburn-producing UV radiation at a particular place and time. It is directly proportional to the intensity of UV radiation that causes sunburn on human skin. A higher UV index value represents a greater risk of sunburn.

Required Inputs

- ✿ Percentage tree cover

Methods Overview

To estimate tree effects on reducing UV radiation, four datasets are required:

- ✿ Canopy cover (from field data)
- ✿ UV index values from Tropospheric Emission Monitoring Internet Service (TEMIS 2016) for the years 2008–2013. TEMIS provides near-real time data on total ozone and surface UV data.
- ✿ Hourly cloud cover from local weather data
- ✿ Solar zenith angle data, calculated internally based on location.

These data are combined with equations (Grant and Heisler 2006, Grant et al. 2002, Heisler et al. 2003a, b) to predict the UV protection factor and changes in the UV index due to trees within each city land use for mid-day conditions for an entire year. Detailed methods are provided in Na et al. (2014).

i-Tree Eco estimates the following factors for each land use and the overall study area based on average tree cover in the land use:

- ✿ Protection factor—a unitless value meant to estimate the UV radiation-blocking capacity of trees. It is comparable to the SPF rating in sunscreen and is calculated as unshaded UV index divided by shaded UV index.

- ✿ Reduction in UV index—the change in UV index as the result of trees and calculated as unshaded UV index minus shaded or overall UV index.
- ✿ Percent reduction—the reduction in UV index expressed as a percentage change and calculated as the reduction in UV index divided by unshaded UV index.

Two types of UV indices are produced:

- ✿ Overall UV index—based on a person in tree shade proportional to the amount of tree cover in the area (average effect). The likelihood of being in the shade increases as tree cover increases.
- ✿ Shaded UV index—based on a person always being in tree shade (maximum effect).

Economic Valuation

Not assessed. Research results on the health values associated with reduced UV radiation need to be incorporated within i-Tree.

Advantages, Uncertainties, and Limitations

i-Tree Eco builds on the equations from Grant et al. (2002) to estimate the below-canopy reduction in UV radiation across a study area. i-Tree Eco provides an easy means to estimate tree impacts on UV radiation that coincides with estimates from other studies and field measurements. However, the uncertainty of the estimates are unknown. Potential limitations are that it assumes the trees are evenly spaced across the landscape, thus shade effects could be overestimated compared to scenarios where all of the tree cover is aggregated together (e.g., in a forest stand). The module also does not include the effects of local aerosols and building shade on altering UV radiation loads in the study area.

Planned Improvements

- ✿ Add health impacts due to reduced UV radiation.

WOOD PRODUCTS

This module estimates the amount and value of wood products (board feet, cords, logs, chips, pallets, firewood) that could potentially be derived from the urban forest based on a 2 percent annual mortality rate (adjusted by d.b.h. class as per i-Tree Forecast methods) using methods detailed in Nowak et al. (2019).

Planned Improvements

- ✿ None

WILDLIFE HABITAT

i-Tree Eco currently estimates wildlife habitat suitability for nine bird species: American robin (*Turdus migratorius*), Baltimore oriole (*Icterus galbula*), black-capped chickadee (*Poecile atricapillus*), Carolina chickadee (*P. carolinensis*), European starling (*Sturnus vulgaris*), northern cardinal (*Cardinalis cardinalis*), red-bellied woodpecker (*Melanerpes carolinus*), scarlet tanager (*Piranga olivacea*), and wood thrush (*Hylocichla mustelina*).

Required Inputs

- ✿ Plot land use
- ✿ Percentage building cover on plot
- ✿ Percentage grass cover on plot
- ✿ Percentage shrub cover on plot
- ✿ Percentage tree cover on plot
- ✿ D.b.h.
- ✿ Total height
- ✿ Crown dieback: percentage crown dieback in live crown area

Methods Overview

Bird habitat models developed by Lerman et al. (2014) are incorporated into i-Tree Eco. Each model predicts a habitat suitability index between 0 and 1, where a score of 0 indicates unsuitable habitat conditions (i.e., strong likelihood the species is not present) and a score of 1 indicates the habitat conditions have a strong likelihood of supporting the species. i-Tree Eco uses a suitability index for each bird species listed above (if the location is within the native range of bird species) under current conditions and also with all trees removed to determine what impact the current forest structure has on habitat suitability. Details and equations are given in Lerman et al. (2014).

Economic Valuation

None. Research is needed on how a value from numerous wildlife species can be modeled and assessed in a local context.

Advantages, Uncertainties, and Limitations

Model results have been compared to field data in Baltimore; these results support the efficacy of using the habitat models to predict the habitat quality of urban areas for a variety of species. However, the model could not be validated for the Baltimore oriole and scarlet tanager model at this time. Still, these untested models have greater value than no information regarding these species' habitat relationships (Lerman et al. 2014). Limitations to the habitat assessment approach are detailed in Lerman et al. (2014).

Planned Improvements

- ✿ Add more wildlife habitat models to i-Tree Eco.
- ✿ Give users the option of selecting pollution stations.

SUMMARY OF UNCERTAINTY AND ECONOMIC VALUATION

Table 4 summarizes the estimation uncertainty of i-Tree Eco. Table 5 summarizes the economic valuation procedures used in i-Tree. Table 6 summarizes the monetary values used in i-Tree. Not all services are valued or assessed in i-Tree (e.g., noise reduction, aesthetics, temperature reduction), so the valuation is conservative. In many cases, users can adjust these values if they have better or more local values.

Table 4.—Summary of estimation of uncertainty in i-Tree Eco

Data	Summary	Estimate
Direct tree measurements: species, d.b.h., crown parameters, percent canopy missing, crown dieback, crown light exposure, direction and distance to building	Assumes measured without error. Percentage missing and dieback are within 5% categories	OK
Leaf area	Based on equations using measured crown parameters. Unknown uncertainty, but likely minimal as crown parameters are measured.	OK based on comparison with measured leaf area index values and field tests (e.g., Peper and McPherson 1998, 2003)
Leaf biomass	Direct conversion from leaf area using species values (g/m ²) leaf area. Unknown uncertainty, but likely minimal as crown parameters are measured.	OK
Tree biomass / carbon	Based on species equations using d.b.h. or d.b.h. and height; unknown uncertainty but likely minimal as tree d.b.h. and height are measured. Addition of wood density information should reduce uncertainty.	OK based on comparison with carbon densities (e.g., Nowak et al. 2013a)
Plot measurements	Assumes measured without error. Percentage cover classes within 5% categories	OK
Sampling error	Reported based on statistical methods	OK
Species diversity	Based on diversity formulas using direct measures	OK
Insect and disease risk	Based on host preference data, pest range maps, and direct field measurements	OK, but maximum potential impact is given
Invasive species	Based on invasive lists for each state and direct field measures	OK, but neighboring state lists are used if state does not have an invasive species list
Structural value	Based on CTLA ^a formulas using direct field measurements	OK, but uses older versions of CTLA formulas and assumes CTLA produces appropriate structural values
Air pollution removal	Based on numerous atmospheric modeling routines. Limitations include limited pollution concentration data (often one local monitor represents concentration for entire area). Health effects are based on BenMAP ^b procedures.	Range of uncertainty of removal is given; produces deposition velocities and daily flux patterns that coincide with measured field data (e.g., Lovett 1994, Morani et al. 2014). Unknown certainty related to health effects
Building energy use	Based on building model estimates and field measures	Uncertainty is unknown but likely high
Avoided emissions	Based on state-specific conversions factors from energy sources	Uncertainty is unknown but likely high due to high uncertainty in energy effects
Carbon sequestration	Based on growth estimates derived from local growing season length, tree condition, and competition	Growth estimates are within range of measured values; uncertainty is likely moderate at the individual tree level but lower for population estimates
Oxygen production	Derived from carbon sequestration estimates	Uncertainty is likely moderate at the individual tree level but lower for population estimates
UV radiation reduction	Based on generalized shading estimates	Uncertainty is unknown but likely high
Wildlife habitat	Based on wildlife habitat models for 9 bird species	Uncertainty is unknown but is likely minimal to moderate
Stream flow	Based on the i-Tree Hydro model	Uncertainty is unknown but likely moderate due to simplified assumptions used as compared with the i-Tree Hydro model
Water quality	Based on event mean concentration data	Uncertainty is unknown but likely high
VOC emissions	Based on standard modeling procedures	Uncertainty is unknown but likely minimal as values closely aligned with standardized values produced by U.S. land use inventory (Kinnee et al. 1997)

^a Council of Tree and Landscape Appraisers.

^b U.S. EPA's Environmental Benefits Mapping and Analysis Program (U.S. EPA 2012).

Table 5.—Summary of valuation methods used in i-Tree

Metric evaluated	Valuation method	User adjustment of values
Structural		
Structural value	Adjusted replacement cost based on CTLA ^a approach	No, unless users supplies local species values that can be integrated within the model
Tree species diversity	Not valued	
Potential insect and disease effects	Uses structural value	No
Invasive species	Not valued	
Ecosystem Service		
Air pollution removal	Average externality values or health care expenses, productivity losses, value of statistical life; Producer price index adjusted. For international estimates, regression equations based on population density can be used	No for health valuation; yes for externality values
Building energy use and emissions	Cost of electricity, cost of fuel; social cost of carbon and methane	Yes, ratio of user value to i-Tree value can be used to adjust value
Carbon storage and sequestration	Social cost of carbon; Producer price index adjusted	Yes, ratio of user value to i-Tree value can be used to adjust value
Oxygen production	None, assigned no value	Yes, user can apply local value per tonne of oxygen
Ultraviolet radiation	Not valued	
Wildlife habitat	Not valued	
Stream flow and water quality	Average cost of storm water control or service fees	Yes, ratio of user value to i-Tree value can be used to adjust value
VOC emissions	Not valued	

^a Council of Tree and Landscape Appraisers.

Table 6.—Summary of dollar values used in i-Tree

Value Type	Approach	Dollar Year		Value	Reference
		Base	Current		
Structural	CTLA	c. 2000	c. 2000	Variable by state	Appendix 7
Air pollution removal	Health values	Variable	Variable	Variable by location (PM _{2.5} , SO ₂ , NO ₂ , O ₃)	U.S. EPA 2012
	Externality	c. 1990	2011	CO=\$1,599/tonne	Murray et al. 1994, Ottinger et al. 1990
Carbon	Social cost (2020; 3% discount rate)	2007	2018	\$188/tonne carbon	Interagency Working Group on Social Cost of Carbon 2016
Energy	Utility costs	2020	2020	Variable by state	Appendix 8
Oxygen	No value	na	na	\$0/t	Nowak et al. 2007b
Water	Average storm water control and treatment	c. 2004	c. 2004	\$0.008936/gallon	McPherson et al. 1999, 2000, 2001, 2002, 2003, 2004, 2006a, 2006b, 2006c, 2007, 2010; Peper et al. 2009, 2010; Vargas et al. 2007a, 2007b, 2008

Other i-Tree Tools

i-Tree Eco is the core tool in assessing forest structure, services, and values. However, other i-Tree tools also assess this information, using data derived from i-Tree Eco procedures (Table 7). The following sections will provide a brief overview of how the tools assess forest structure and services.

I-TREE CANOPY

i-Tree Canopy uses Google aerial images of the study area to produce statistical estimates of tree and other land cover types, such as grass, structures, and impervious surfaces. Random points are placed in the defined area of interest and the user identifies the land cover class at the point center. Cover classes are defined by the user. Statistical estimates of area in each cover class (as a percent) are calculated as:

$$\% = n / N$$

Where

n = number of point hitting the cover class, and

N = total number of points analyzed among all cover classes.

The standard error (SE) of the estimate is calculated as:

$$SE = \sqrt{(pq/N)}$$

Where

p = n/N, and

q = 1 – p (Lindgren and McElrath 1969).

Percentage tree cover is multiplied by the area analyzed to determine the total tree cover area.

Table 7.—Relationship of other i-Tree tools with the core i-Tree Eco program

Incorporated within i-Tree Eco	Values derived from i-Tree Eco methods	Independent tool (no relationship with i-Tree Eco)
Forecast	Canopy ^a	Cool Air
Hydro ^b	County ^a	Cool River
Streets	Design	Harvest
	Landscape ^{a,c}	Wood Marketplace
	MyTree	
	OurTrees ^a	
	Planting	
	Projects ^d	
	Species ^c	

^a Uses derived values per area (m²) of tree cover for U.S. census places.

^b Some of i-Tree Hydro's routines are incorporated into i-Tree Eco.

^c Will link to i-Tree Eco in the future.

^d Displays i-Tree Eco results and data.

If the number of points classified in a category (n) is less than 10, a different SE formula (Poisson) is used as the normal approximation cannot be relied upon with a small sample size (<10) (Hodges and Lehmann 1964). In this case:

$$SE = (\sqrt{n}) / N$$

More detailed information and examples are given in Nowak (2011).

Estimates of air pollution removal, carbon sequestration, and hydrologic impacts are based on the area of tree cover. A local standardized removal rate (e.g., kg/m² of tree cover) is multiplied by local tree cover (m²) from i-Tree Canopy to estimate a total effect from the trees (kg). For air pollution removal, i-Tree Eco used air pollution and weather data to estimate average pollution removal effect per unit of tree cover (g/m² or \$/m² of tree cover) for each U.S. county. Detailed methods regarding this process are given in Hirabayashi and Nowak (2016) and Nowak et al. (2014).

Estimates of carbon storage and annual sequestration are based on national and state data and methods from Nowak et al. (2013a). National standardized value of carbon storage per area of tree cover (7.69 kg C/m²) are applied to the tree cover amount to estimate carbon storage. State-specific values (kg C/m² tree cover/year) are used to estimate carbon sequestration. These values vary based on length of growing season (Nowak et al. 2013a).

Estimates of avoided runoff, transpiration, and rainfall interception are based on the area of tree cover and local weather data. A local standardized removal rate (e.g., m³ water/m² of tree cover) is multiplied by local tree cover (m²) from i-Tree Canopy to estimate a local total effect from the trees (m³). For hydrologic estimates, i-Tree Eco used weather data to estimate average effects per unit of tree cover (m³/m² or \$/m² of tree cover) for each U.S. county. Detailed methods regarding this process are given in Hirabayashi (2015).

Planned Improvements

- ✿ Update standardized carbon and pollution values.

I-TREE COOL RIVER

i-Tree Cool River is a mechanistic model that simulates the effects of riparian shading and impervious runoff on river temperatures. This model code is available under the research suite and model methods are detailed in Abdi and Endreny 2019 and Abdi et al. 2020.

Planned Improvements

- ✿ None.

I-TREE COUNTY

i-Tree County is a tool based on data and methods in i-Tree Landscape. This tool allows users to quickly estimate ecosystem services and values from trees in an entire U.S. county or for a smaller area based on inputs of the area of tree cover.

Planned Improvements

- ✿ Update values as i-Tree Landscape values are updated.

I-TREE DESIGN

i-Tree Design links to Google maps and allows a user to sketch the outline of their home and estimate how the trees around their home affect energy use and savings, and other environmental services of carbon sequestration, air pollution removal, and rainfall interception. Effects are projected over time based on methods from i-Tree Forecast, which projects tree size through time. Growth effects are projected both into the future and back in time to estimate cumulative effects to date.

Building energy conservation effects and carbon storage/sequestration are based on the methods detailed for i-Tree Eco. Air pollution removal, rainfall interception, and avoided stormwater runoff are calculated based on methods detailed in i-Tree Canopy using the tree's canopy area. In addition, pollution removal also incorporates tree species information (deciduous vs. evergreen) and tree leaf area index calculations to improve the estimates. These variable removal rates by leaf area were determined by running the i-Tree Eco model for every U.S. county using LAI values ranging from 0 to 18, in 0.5 increments. Storm water abatement values (\$/gallon) are calculated from the i-Tree Streets Reference City Community Tree Guides, a collection of documents, primarily published by the Forest Service, available at <http://www.itreetools.org/resources/archives.php>.

Planned Improvements

- ✿ Add information related to invasiveness of species and insect and disease risks.
- ✿ Link to i-Tree Species and i-Tree Landscape to provide management guidance related to tree species selections and locations.

I-TREE FORECAST

i-Tree Forecast simulates future forest structure (e.g., number of trees and sizes) and various ecosystem services based on annual projections from the current forest structure data obtained from i-Tree Eco. There are three main components of i-Tree Forecast:

- ✿ Tree growth: projects annual growth for tree diameter, crown size, and leaf area for each tree.
- ✿ Tree mortality: projects annual mortality based on user-defined mortality rates.
- ✿ Tree establishment: projects annual new tree populations as input by users; can be used to illustrate the effect of the new trees or determine how many new trees need to be added annually to sustain a certain level of tree cover or benefits.

Tree Growth

Annual tree diameter growth is estimated for the study area based methods detailed in the carbon storage and sequestration section. i-Tree Forecast estimates tree height, crown width, crown height, and leaf area based on tree diameter for each future year. Tree height, crown height, and crown width are calculated using species, genus, order, and family specific equations that were derived from measurements from urban tree data ([appendix 13](#)). If tree height, crown height, or crown width data are not collected in i-Tree Eco, these equations are used to estimate the missing input values. They are also used to estimate crown parameters in i-Tree Design and MyTree. If there is no equation for a particular species, then the genus equation is used, followed by the family and order equations, if

necessary. If no order equation is available, we use an equation for all trees to estimate these parameters. Projected leaf area is calculated from the crown height, tree height, and crown width estimates based on i-Tree methods ([see Leaf Area and Leaf Area Index](#)).

Projected canopy cover is calculated by summing the two-dimensional crown area of each tree in the population.

Tree Mortality Rate

Canopy dieback is the first indicator for tree mortality. Trees with 50 to 75 percent crown dieback have an annual mortality rate of 13.1 percent, trees with 76 to 99 percent dieback have a 50 percent annual mortality rate, and trees with 100 percent dieback have a 100 percent annual mortality rate (Nowak 1986). Trees with less than 50 percent dieback have a user-defined mortality rate based on the tree size class and diameter.

Trees are assigned to species-size classes: small trees have an average height at maturity of less than or equal to 12.2 m (40 ft) (maximum diameter class = 50.8+ cm [20+ inches]); medium trees have mature tree height of 12.3 to 18.3 m (41 to 60 ft) (maximum diameter = 76.2+ cm [30+ inches]); large trees have a mature height of greater than 18.3 m (60 ft) (maximum diameter = 101.6 cm [40+ inches]). Each size class has a unique set of seven diameter ranges to which base mortality rates are assigned based on measured tree mortality by diameter class (Fig. 14) (Nowak 1986). The same distribution of mortality by diameter class is used for all tree-size classes, but the diameter range of the classes differed by size class. The actual mortality rate for each diameter class is adjusted so that the overall

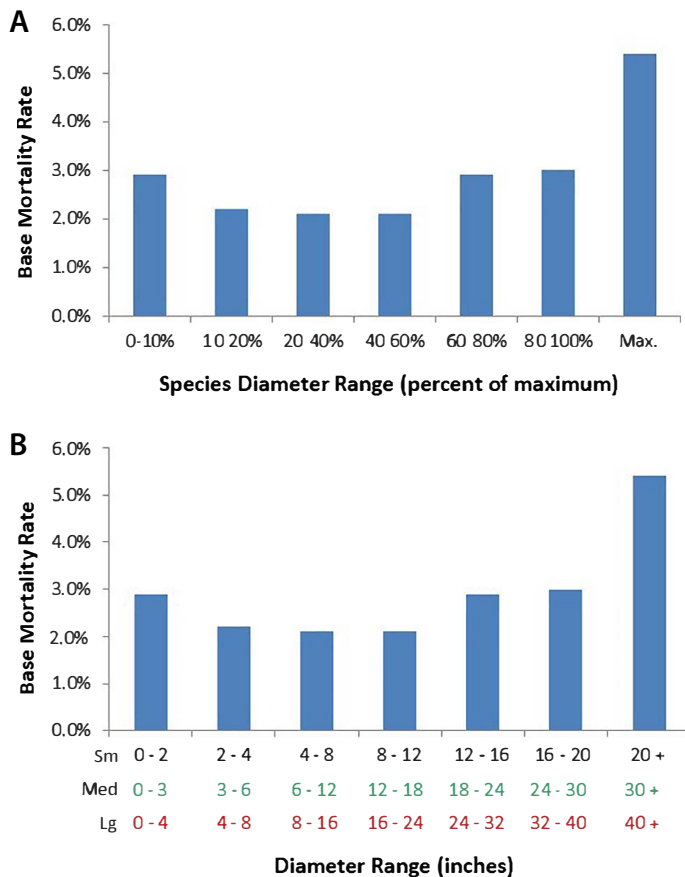


Figure 14.—(A) Mortality rate distribution by diameter class (d.b.h.) with d.b.h. range classified by the percent of maximum d.b.h. for the species; and (B) mortality rates for actual d.b.h. classes for small, medium, and large tree species.

average mortality rate for the base population equaled the mortality rates assigned by the user. That is, the relative curve of mortality stays the same among diameter classes, but the actual values change based on the user-defined overall average rate. If desired, users can set custom mortality rates for individual genera, condition classes, or strata.

Forecasting

i-Tree Forecast classifies the population into tree species and diameter cohorts (e.g., all 5-cm red maples are one cohort). Based on estimated growth rates for the species and study area, the computer model simulates annual tree population totals by “growing” and “killing off” part of each cohort based on the user-defined mortality rates. The original stem diameter of newly established trees is input by the user. New cohorts are added based on user-defined annual planting rates. In simulating the annual addition of new trees to the model, the species composition of new trees is assumed to be proportional to the current species composition. New trees are assigned a crown light exposure (CLE) of 5 for leaf area calculations and the average CLE from the existing population for growth rate calculations. Total population numbers and characteristics (e.g., d.b.h., leaf area, tree cover) are determined for each year of the projection by summing the values from the individual cohorts.

Projected ecosystem services are estimated for carbon storage and air pollution removal. Carbon storage is based on the carbon equations and processes from i-Tree Eco. Pollution removal is based on county removal rates (g/m² of tree cover) from i-Tree Canopy, but with variable pollution removal rates based on the LAI. These variable rates are determined by running the i-Tree Eco model for every U.S. county using LAI values ranging from 0 to 18, in 0.5 increments. The projected LAI for each year is calculated as:

$$LAI = LA_p / TC_p$$

Where

LAI = leaf area index per unit tree cover,

LA_p = projected leaf area (m²) for the population, and

TC_p = projected tree cover (m²) for the population study area.

The annual LAI values are then used to estimate the annual pollution removal by multiplying the appropriate removal rate based on LAI (g/m² tree cover) by area (m²) of projected tree cover.

Extreme Events

Users can choose to simulate potential changes due to insect or disease outbreaks or storm events. Users can select an individual insect or disease, what year the outbreak will occur, how long the outbreak will last and what mortality would be expected from the outbreak. Based on the selections, only species susceptible to the outbreak would be killed at the assigned rate. Also, susceptible species would not be planted in the projections, unless the option to plant these species is selected by the user. For storm events, the user can select the storm type (e.g., class 1 hurricane), year of the event, and whether to use default or custom mortality rates for the event. Based on the selection, all trees would be killed during the event based on the assigned mortality rate.

Planned Improvements

- ✿ Update mortality rates based on field data from monitoring of plot data.
- ✿ Develop a tree establishment rate to sustain desired level of tree cover.

I-TREE HARVEST

i-Tree Harvest allows land managers to estimate the amount of carbon stored in harvested wood products; the estimating method was originally known as the PRESTO Wood Calculator. This tool calculates carbon values based on methods detailed in Smith et al. (2006) and does not use i-Tree methods.

Planned Improvements

- ✿ None.

I-TREE HYDRO

i-Tree Hydro is designed to assess hourly changes in water quantity and quality due to changes in tree and other land cover types within a watershed or nonwatershed area. i-Tree Hydro calculates hourly interception, evapotranspiration, runoff, and other hydrologic values based on a semi-distributed, mechanistic rainfall-runoff computer model. Interception is simulated using an improved Rutter methodology (Valente et al. 1997) and evapotranspiration is simulated using improved Penman-Monteith equations (e.g., Shuttleworth 1993). More detailed methods for those and other parts of the model water budget are given in Wang et al. (2008), Yang et al. (2011) and Yang and Endreny (2013). Hydrological parameters of the model can be calibrated to produce the best fit between predicted and observed streamflow. Water quality impacts are also simulated based on national and localized event mean concentration (EMC) pollutant coefficients.

Hourly weather data are derived from the weather station located closest to the study area and are preprocessed as described in Hirabayashi and Endreny (2016). Tree, grass, and impervious land cover percentages for a watershed are derived from i-Tree Canopy, i-Tree Eco, satellite data, or other means. The model can be calibrated for watershed areas using hourly stream flow data with model-independent parameter estimation analysis calibration routines (Wang et al. 2008). Calibration coefficients are calculated for peak flow, base flow, and balance flow (peak and base). A coefficient of +1 indicates a perfect fit to the model, 0 indicates the model predicts the same as the mean value, and a negative indicates that using the mean is a better predictor than the model (Moriassi et al. 2007). Differences between measured and estimated flow can be substantial due to mismatching of stream flow and weather data, as the weather stations are often a distance away from the watershed area. For example, it may be raining at the weather station and not in the watershed or vice versa. Default parameters are provided as a starting point for calibration or for use in projects where calibration is not desired or possible.

Leaf area index (LAI) is estimated as 4.7 for trees, 2.2 for shrubs, and 1.6 for herbaceous cover. The percentage impervious cover connected to the stream (known as directly connected impervious area or DCIA) varies with percentage impervious cover estimated for land cover determinations, with percentage connected increasing as percentage impervious cover increases (Sutherland 2000). The percentage of directly connected impervious cover represents the portion of impervious cover that drains directly to

the modeled stream or any of its tributaries. The phrase “drains directly” describes a situation where precipitation that falls on a portion of the watershed’s impervious cover is conveyed, overland or through a storm sewer network, directly into the stream or its tributaries.

Water Quality Effects

Event mean concentration (EMC) data are used for estimating pollutant loading into watersheds. The EMC is a statistical parameter representing the flow-proportional average concentration of a given parameter during a storm event and is defined as the total constituent mass divided by the total runoff volume (M/V). Estimates of EMC are usually obtained from a flow-weighted composite of concentration samples taken during a storm. Mathematically (Charbeneau and Barretti 1998, Sansalone and Buchberger 1997):

$$EMC = \bar{C} = \frac{M}{V} = \frac{\int C(t) Q(t) dt}{\int Q(t) dt} \approx \frac{\sum C(t) Q(t) \Delta t}{\sum Q(t) \Delta t}$$

Where

$C(t)$ and $Q(t)$ are the time-variable concentration and flow measured during the runoff event, and

M and V are pollutant mass (typically in milligrams) and runoff volume (typically in liters).

EMC results are from a flow-weighted average, not simply a time average of the concentration. Data from EMCs are used for estimating pollutant loading into watersheds.

The pollution load calculation from the EMC method is:

$$L = EMC \times Q = EMC \times d_r \times A$$

Where

L is the pollutant load in mass per unit time (such as mg/h),

EMC is event mean concentration (such as mg/l, or mg/m³, etc.),

Q is surface runoff per time period associated with EMC (such as l/h, m³/day, etc.),

d_r is runoff depth per time period associated with EMC and study area (such as mm/h, m/h, m/day), and

A is the study area (m²), which is the catchment area in i-Tree Hydro.

The EMC is multiplied by the runoff volume to estimate the pollution load to the receiving water. Under most circumstances, the EMC provides the most useful means for quantifying the level of pollution resulting from a runoff event (U.S. EPA 2002).

Data from the three sources are used to compute estimates of EMC means and medians for 10 pollutants (Table 8): Nationwide Urban Runoff Program (U.S. EPA 1983), U.S. Geological Survey [USGS] urban storm water runoff database (Driver et al. 1985), and National Pollutant Discharge Elimination System (Smullen et al. 1999). These estimates are based on nationwide data and do not account for regional variation in soil types, climate, and other factors.

Table 8.—National pooled EMC values used in i-Tree Hydro

Constituent	EMCs (mg/l)		No. of Events
	Mean	Median	
Total suspended solids (TSS)	78.4	54.5	3,047
Biochemical oxygen demand (BOD)	14.1	11.5	1,035
Chemical oxygen demand (COD)	52.8	44.7	2,639
Total phosphorus (TP)	0.315	0.259	3,094
Soluble phosphorus (Soluble P)	0.129	0.103	1,091
Total Kjeldhal nitrogen (TKN)	1.73	1.47	2,693
Nitrite and nitrate (NO ₂ and NO ₃)	0.658	0.533	2,016
Copper (Cu)	0.0135	0.0111	1,657
Lead (Pb)	0.0675	0.0507	2,713
Zinc (Zn)	0.162	0.129	2,234

The new i-Tree Hydro program in the research suite (i-Tree Hydro+) also estimates air temperature changes due to trees and impervious surfaces based on methods detailed in Yang et al. (2013).

Planned Improvements

- ✦ Add mean and median pollutant coefficients specific to each hydrologic unit code (HUC) 8¹⁰ and National Land Cover Database (NLCD) class (Homer et al. 2015) for sediment, total nitrogen, and total phosphorus (White et al. 2015).
- ✦ Include green infrastructure impacts.
- ✦ Add spatially-explicit land cover inputs and processing.
- ✦ Add analyses of nutrient “hot spots” of nitrogen and phosphorus to identify areas to mitigate these chemicals (Stephan and Endreny 2016).

I-TREE LANDSCAPE

i-Tree Landscape integrates national landscape and environmental data to aid in forest management and planning. Users can explore tree and impervious cover, land cover, and basic demographic information. Users can also assess the benefits and values of trees (carbon storage, air pollution removal, reduced storm water runoff) in their area; understand local risks to people and forests (insects and diseases, wildfire potential, wildland-urban interface, forest basal area and composition, ultraviolet radiation exposure, air pollution exposure and areas of poor air quality, surface temperatures, projected climate change, brownfields, hardness zones, flood and riparian zones, projected urban development, impaired waterways, tree species shifts due to climate change); and map areas to prioritize tree planting or protection efforts that improve forest and human health. i-Tree Landscape provides the details on the sources for the various forest, population, and risk data.

¹⁰ HUC 8 refers to maps at the sub-basin level, analogous to medium-sized river basins. There are about 2200 nationwide.

The program displays maps and associated data, as well as allows for prioritization among data sets to select the best areas for management among user-selected management units across the country. Management units include:

- ✿ State
- ✿ County
- ✿ County subdivision
- ✿ U.S. Congressional Districts
- ✿ Census places (e.g., cities) (U.S. Census Bureau 2010a)
- ✿ Census block groups (U.S. Census Bureau 2010a)
- ✿ Hydrology units/HUC 12¹¹ watersheds (U.S. EPA and USGS 2012)
- ✿ Federal lands (National Atlas of the United States 2014) , including
 - Native American reservations
 - Bureau of Land Management, subdivided into:
 - U.S. conservation areas
 - National monuments
 - U.S. recreation areas
 - U.S. wilderness areas
 - Public domain lands
 - Bureau of Reclamation
 - Department of Defense, subdivided into:
 - Air force
 - Army
 - Marine corps
 - Navy
 - Other
 - Department of Energy
 - Department of Agriculture, Forest Service (USDA Forest Service 2015, 2016), subdivided into:
 - National forests
 - Ranger Districts
 - National grasslands
 - National wilderness areas
 - Collaborative Forest Landscape Restoration (CFLR) project boundaries
 - Other
 - Fish and Wildlife Service, subdivided into:
 - National wilderness areas

¹¹ HUC 12 is a local, subwatershed level that captures tributary systems, about 90,000 nationwide.

- National wildlife refuges
- Other
- National Park Service, subdivided into
 - National monuments
 - National parks
 - National preserves
 - National recreation areas
 - National wilderness areas
 - Other

Based on 2011 tree and impervious cover data from the National Land Cover Database (NLCD) (U.S. Geological Survey 2014) or locally supplied high resolution tree and impervious cover maps (<https://landscape.itreetools.org/hires>), along with other local data, the following ecosystem services for trees or environmental data in each area of analysis are assessed:

Air Pollution Removal

Air pollution removal and value estimates are based on procedures detailed in Nowak et al. (2014). This process uses local tree cover, leaf area index, percentage evergreen trees, weather, pollution, and population data to estimate pollution removal (g/m² tree cover) and values (\$/m² tree cover) in urban and rural areas for each county. These values are applied to the area of tree cover to determine estimated removal and associated values of carbon monoxide (CO), nitrogen dioxide (NO₂), ozone (O₃), particulate matter less than 2.5 microns (PM_{2.5}), particulate matter between 2.5 and 10 microns (PM₁₀*), and sulfur dioxide (SO₂). Value estimates are based on local health impacts estimated using U.S. EPA BenMAP (U.S. EPA 2012) model for each U.S. county for all pollutants except for CO and PM₁₀*, which use externality values (\$/t) to estimate pollutant removal value. Estimated health impacts from changes in concentrations of NO₂, O₃, PM_{2.5} and SO₂ due to trees are also provided based on BenMAP methodology (U.S. EPA 2012).

Estimates of pollution removal vary by county.¹² Average county removal rates are used, but have a maximum and minimum value. Average differences from the mean vary from a low of 30 percent for NO₂ to a high of 106 percent for PM_{2.5}. The maximum and minimum values are likely unreasonable values as they assume a maximum or minimum removal rate for every hour of the year. No maximum or minimum values are estimated for CO.

Carbon Storage and Annual Sequestration

These values are calculated from two separate sources depending upon location (NLCD land cover class).

Nonforest carbon: For nonforest NLCD classes, total carbon storage and net annual sequestration are estimated using values estimated from urban forests (Nowak et al. 2013a). Net annual sequestration is an estimate of carbon accumulation from tree growth minus estimated carbon lost through decomposition due to tree mortality. Carbon

¹² See online dataset for county-level estimates at https://www.itreetools.org/landscape/resources/Landscape_air_pollutant_removal_ranges.xlsx

storage is estimated based on the national average storage value of 7.69 kg C/m² tree cover (standard error [SE] = 1.36 kg C/m²). Net sequestration is based on state-specific estimates that vary based on length of growing season and average = 0.226 kg C/m² tree cover/yr [SE = 0.045 kg C /m² tree cover/yr]). State-specific values vary from 0.430 kg C/m² tree cover/yr (Hawaii) to 0.135 kg C/m² tree cover/yr (Wyoming) (Nowak et al. 2013a). These values are applied to the tree cover estimates (m²) from the tree cover map to estimate total carbon (kg).

Forest carbon: For forested regions, total carbon storage and net annual sequestration are derived from USDA Forest Service Forest Inventory and Analysis (FIA) data for each U.S. county. Net annual sequestration is calculated as carbon accumulated annually between FIA remeasurements based on accumulation from tree growth and new trees, minus carbon lost through tree mortality. The estimation of sequestration in forests is based on field measurements of change including the addition of new trees and loss of existing trees. In nonforest areas, net sequestration is estimated from computer models and is based on tree growth of existing trees and estimated mortality based on tree condition over a 1-year period. The nonforest sequestration estimate does not include the addition of new trees and includes only a partial loss of carbon from mortality due to decomposition (entire carbon from trees is not removed, only part of carbon lost to decomposition is removed).

Total carbon storage and net carbon sequestration per hectare of land is converted to total carbon storage and net sequestration per hectare of tree cover by dividing the carbon per hectare by percentage tree cover of the forested land in the county. Tree cover estimates from NLCD forest classes are used. In U.S. counties where tree cover is less than 10 percent (19 counties), tree cover is set to 10 percent to avoid inflating carbon density values. If no FIA carbon storage data exists for a county, but the county has tree cover within NLCD forest land, carbon storage density from the closest county is used. FIA carbon storage densities average 6.3 kg C/m²; carbon storage density adjusted for tree cover equals 9.8 kg C/m² tree cover. The average SE associated with these estimates is 1.3 kg C/m² tree cover.

As NLCD forest land estimates (197 million hectares) are less than FIA forest land (264 million hectares), all estimates derived for forest land in i-Tree Landscape will be lower than FIA estimates. For example, FIA-defined forest land stores 16.7 billion metric tons of carbon in the conterminous United States but estimates from NLCD-defined forest land shows 13.3 billion metric tons of carbon. FIA forest land and carbon estimates are about 25 percent more than those derived using NLCD data due to differences in definition and classification of forest land between FIA and NLCD. i-Tree Landscape uses NLCD for the classification of forest area.

Net sequestration per area of tree cover is calculated in the same manner as for carbon storage. For net carbon sequestration, values for some counties are missing. If a county had a missing value, sequestration density values (kg C/m² tree cover/yr) from nearby counties in the same state are used. If the entire state had missing values, the county sequestration value is estimated based on converting the national FIA sequestration density value from all known counties to state values based on the ratio of state sequestration densities to national sequestration density for nonforest areas:

Forest sequestration density for state = national average forest sequestration density x (state nonforest sequestration density / national average nonforest sequestration density).

This procedure was used for net forest sequestration in many western states (Arizona, California, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, Wyoming). The average net sequestration value for forests is 0.14 kg C/m² tree cover/yr (average SE = 0.10 kg C/m² tree cover/yr) (https://www.itreetools.org/landscape/resources/Carbon_storage_and_seq_by_county_FIA.xlsx). This value is about 60 percent of the nonforest sequestration value. This difference is likely due to increased growth rates in urban areas (due to more open-grown nature of trees) and differences in means of calculating net sequestration (forest estimates remove all carbon from trees that die, but in urban estimates only a small portion are removed).

The value of carbon storage and sequestration is estimated at \$188/metric ton of carbon. This value is derived from the Interagency Working Group (2016).

Hydrologic Effects

Estimates of evaporation, transpiration, precipitation interception, and avoided runoff for each county in the conterminous United States in 2010 were developed using i-Tree Eco, local leaf area indices, and weather data. Methods are detailed in Hirabayashi (2016) and Hirabayashi and Endreny (2016). The standard errors on these estimates are unknown.

Input data are estimates from a primary source (e.g., tree and impervious cover estimates come directly from NLCD). Ecosystem services and value estimates are derived as secondary estimates from the input data and other sources. The primary data layer used is tree cover, thus limitations in this layer will affect ecosystem service estimates (Table 9).

In addition to ecosystem services, other data were processed to produce environmental layers.

Table 9.—Summary of estimation uncertainty in i-Tree Landscape

Input Data	Summary	Estimate
NLCD tree cover	10% average underestimate per area in 2001 (Nowak and Greenfield 2010); unknown but likely underestimate in 2011	Conservative estimate
High resolution tree cover	Likely within a few percentage points	OK- Errors are believed to compensate
NLCD impervious cover	Possible minor (~1%) underestimate of impervious cover (Nowak and Greenfield 2010)	OK
NLCD land cover	Accuracy between 80–90% (Wickham et al. 2013, 2017)	OK
Census Data	Accurate – based on census	OK
Carbon storage	National average C density from urban areas are used for nonforest areas (relative SE of 17.7%); County carbon density from FIA data are used for forest areas (relative SE of 13.3%)	Conservative estimate if using NLCD tree cover
Carbon sequestration	State average carbon sequestration density from urban areas used for nonforest areas (relative SE of 19.9%); Estimated county carbon sequestration density from FIA data (not all counties had values) used for forest areas (relative SE of 71.4%)	Conservative estimate if using NLCD tree cover
Air Pollution removal	County pollution removal estimates; maximum and minimum values are on average within 57% of the mean	Conservative estimate if using NLCD tree cover
Hydrology	Estimates based on local weather and leaf area indices; error is unknown	Conservative estimate if using NLCD tree cover

Air pollution exposure and areas of poor air quality:

The average and maximum PM_{2.5} values, and maximum ozone values for all days in 2008 were obtained from the U.S. EPA downscaler model (U.S. EPA 2008) and classified as:

- ✿ Good (4–6 µg/m³ for PM_{2.5} and 50–54 ppb for ozone)
- ✿ Moderate (7–9 µg/m³ for PM_{2.5} and 55–70 ppb for ozone)
- ✿ Unhealthy for sensitive groups (10–12 µg/m³ for PM_{2.5} and 71–85 ppb for ozone)
- ✿ Unhealthy (13–15 µg/m³ for PM_{2.5} and 86–105 ppb for ozone)
- ✿ Very unhealthy (16+ µg/m³ for PM_{2.5} and 106+ ppb for ozone)

Predicted changes in future ozone concentrations between current conditions (2005) and 2050 were derived from Weaver et al. (2009). The mean future-minus-present MDA8 O₃ concentration differences across six experiments were used.

EPA nonattainment areas (2016) for several pollutants were obtained from the U.S. EPA Green Book (2017b).

Bird Species Richness

The estimated number of bird species were derived from BirdLife International (2020). The following modifications to this dataset were conducted by Curt Flathers, USDA Forest Service:

The original eastern towhee (*Pipilo erythrophthalmus*) showed the ranges for both the eastern and spotted towhee (*Pipilo maculatus*); two range maps were created to reflect each species.

The original least flycatcher (*Empidonax minimus*) did not show the breeding range extending down the northeast United States along the Appalachian Mountains; ranges were modified to correct this omission.

Brownfields

A brownfield is a property with the presence or potential presence of a hazardous substance, pollutant, or contaminant. Locations of brownfields were obtained from the U.S. EPA (2018c).

Climate Change Data

Projected climate data were obtained from the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM) projections (National Center for Atmospheric Research 2016). These data were obtained at a 4.5 km resolution that covered the conterminous United States, but were resampled for display/analysis at 30 m resolution and projected to WGS 1984 Web Mercator Auxiliary Sphere.

Data represented an “ensemble average” of six model runs for representative concentration pathways (RCP) 4.5 and 8.5 for decades starting in 2010 and ending in 2100 (i.e., 2010, 2020, 2030, ... 2100). These data include both the projected values and the differences between current (2010) and future decadal modeled values for annual mean air temperature, annual total precipitation, and mean January and July temperatures.

Drought

Drought information is based on the Cumulative Drought Severity Index (1987–2013) (Peters et al. 2014). The cumulative drought severity index (1987–2013) was categorized as:

- ✿ <50 (limited)
- ✿ 51–100
- ✿ 101–150
- ✿ 151–200
- ✿ 201–250
- ✿ >250 (chronic)

Endangered Species

Number of threatened, endangered, and species of concern for both plants and animals were derived from the U.S. Fish and Wildlife Service (2018).

Flood and Riparian Zones

Riparian zones (i.e., water areas plus the land area within 108 m of surface water edges, 2018) and 100-year floodplain (2016) areas were obtained from EnviroAtlas (U.S. EPA 2018b).

Forest Basal Area and Composition

Forest basal area data by tree species (2012) were obtained from the USDA Forest Service's Individual Tree Species Atlas parameter maps (Ellenwood et al. 2015).

Forest Type

National forest type data were obtained from the USDA Forest Service FSGeodata clearinghouse (USDA Forest Service 2004).

Future Plant Hardiness and Heat Zones

Future plant hardiness and heat zones (Matthews et al. 2018, 2019) are given for three time periods (2010–2039, 2040–2069, 2070–2099) for two model scenarios (CCSM4 under RC4.5 concentration pathway, GFDL CM3 under RC8.5 concentration pathway). Future heat was quantified as the number of days per year with a maximum daily temperature ≥ 30 °C (86 °F). These heat days were also calculated for 1980–2009 and the differences between these base years and the three sets of future years are reported.

Hardiness Zones

The 2012 USDA Plant Hardiness Zone Map is based on the average annual minimum winter temperature, divided into 10-degree Fahrenheit zones (Daly et al. 1990).

Human Populations

Information on human population and housing statistics were derived from the U.S. Census Bureau (2010b).

Impaired Waterways








Impaired waters are waters that are too polluted or otherwise degraded below state water quality standards. Data on impaired waterways were obtained from U.S. EPA (2018a).

Insects and Diseases

Insect and disease range maps from 2017 were obtained from the Forest Health Technology Enterprise Team (USDA Forest Service 2017).

Land Surface Temperature

Land surface temperatures were estimated for the United States as described below.

-  **Landsat scene selection.** Landsat 8 scenes were downloaded from the U.S. Geological Survey (USGS) (U.S. Geological Survey 2013) for the United States and U.S. territories that were as cloud-free as possible (June, July, August) for the years 2013, 2014, and 2015. Scenes were selected to provide total U.S. coverage for each year. As scenes overlapped, many areas had two or more scenes covering a location.
-  **Converting scene data to surface temperatures.** Landsat 8 thermal infrared sensor band values were converted to land surface temperature by:
 -  Converting satellite data to at-satellite brightness temperature based on equations detailed in U.S. Geological Survey (2017).
 -  Calculating emissivity values from normalized difference vegetation index (NDVI) using the NDVI thresholds method (Sobrino et al. 2001).
 -  Converting at-satellite brightness temperature and emissivity information for each 30 m pixel to Land Surface temperature based on equations given in section 3.4 in Weng et al. (2004).
-  **Cloud and snow removal.** To remove the existing clouds from the images, Fmask (Function of mask) software was used (<https://github.com/prs021/fmask>). Fmask masks clouds, cloud shadows, and snow for Landsat TM/ETM+ images. Pixels where clouds were removed were converted to “no data.”
-  **Land surface temperatures and temperature differences.** Land surface temperatures were estimated for the United States based on Landsat 8 data and standard procedures from the literature. As Landsat scenes had various dates across the United States, each Landsat scene was processed independently to minimize the effect of different scene dates on surface temperatures. To standardize the land surface temperature estimates, the Landsat scene’s median land surface temperature was subtracted for each pixel land surface temperature value to create a relative surface temperature difference estimate. With this approach, about half of scene pixels will have above-median temperatures and half will have below-median temperatures, but the amount they differ from the mean will vary based on local land surface temperatures.

Within each year’s data (e.g., 2015) all scenes were mosaicked and where scenes overlapped, an average of surface temperature differences among the multiple scenes was used to calculate the surface temperature difference at each pixel with multiple values.

To help fill in for “no data” pixels due to clouds or snow, data from the various years (2013–2015) were used. The first priority was given to data from 2015. If “no data” pixels existed in 2015, data from 2014 were used to fill in these missing pixels. If “no data” pixels existed in 2015 and 2014, data from 2013 were used to fill in these missing pixels. If “no data” pixels existed in 2015, 2014 and 2013, these pixels were labeled as “no data.” Land surface temperature difference are projected at 90 meter resolution in i-Tree Landscape.

Projected Urban Development

Projected urban development was mapped based on the Integrated Climate and Land-Use Scenarios version 2.1 of the Fourth National Climate Assessment (U.S. EPA 2018d). These data were modified and generalized from 18 original land use codes to five generalized land uses as follows:

- ✦ Water: natural waters, reservoirs and canals.
- ✦ Wooded: wetlands, recreation or conservation, timber.
- ✦ Nonwooded: grazing, pasture, cropland, mining/barren land.
- ✦ Exurban: parks and golf courses, exurban low density, exurban high density, suburban, institutional.
- ✦ Urban: urban low density, urban high density, commercial, transportation.

Projected changes from 2010 to 2060 and 2100 were mapped for the following class changes to illustrate and calculate areas that are projected to be developed:

- ✦ Nonwooded to exurban
- ✦ Nonwooded to urban
- ✦ Wooded to exurban
- ✦ Wooded to urban

Redline Data

Between 1935 and 1940, thousands of areas were delimited by the federal government’s Home Owners’ Loan Corporation (HOLC). HOLC assigned grades to delimited residential neighborhoods reflecting “mortgage security” that were visualized on color-coded maps. Four mortgage security risk classes were developed. Class A, the highest grade (best), was colored green and were deemed as a minimal risk for lenders. Class B (still desirable) was colored blue, Class C (declining) was colored yellow, and the lowest grade, Class D, was colored red and considered “hazardous” (Nelson et al. 2020).

Sea Level Rise

The area submerged by sea level rise (NOAA 2017) of 1 to 6 feet, at 1-foot increments, are provided.

Storm Surge

Storm surge data (Zachry et al. 2015) for average depth of storm surge and average area submerged by the storm surge are provided, by hurricane category (1-5).

Street Walkability

The U.S. EPA's Walkability Index (U.S. EPA 2015) characterizes every Census 2010 block group in the United States based on its relative walkability. Walkability depends upon characteristics of the built environment that influence the likelihood of walking being used as a mode of travel. The index ranges between 1 and 20 and were categorized as:

- ✿ 1–5.0 (least walkable)
- ✿ 5.1–10.0 (below average walkable)
- ✿ 10.1–15.0 (above average walkable)
- ✿ 15.1–20.0 (most walkable)

Tree Species Shifts Due to Climate Change

To illustrate and calculate projected habitat changes for 314 tree species, we use data from the ForeCASTS Project (North Carolina State University 2018). Current species range maps were contrasted with projected species ranges in 2050 and 2100 based on the Hadley, Scenario A1 climate projection model. Each ~4 km pixel was classified based on the probability of presence for each tree species in each year. The differences in probability between the years was standardized to values between -100 (the species had 100 percent probability in the current year, but 0 probability in the future) and 100 (the species had 0 percent probability in the current year, but 100 probability in the future).

Ultraviolet Radiation Exposure

The average and maximum UV index at local solar noon for all days between 2008 and 2013 were obtained from the Tropospheric Emission Monitoring Internet Service (TEMIS 2016). The UV index is an estimation of the UV levels that are important for the effects on the human skin, where 1 unit equals 25 mW/m². The index ranges from 0 to greater than 11:

- ✿ 0–2: Low UV exposure (damage to skin in >60 minutes).
- ✿ 3–5: Moderate UV exposure (damage to skin in 45 minutes).
- ✿ 6–7: High UV exposure (damage to skin in 30 minutes).
- ✿ 8–10: Very high UV exposure (damage to skin in 15 minutes).
- ✿ 11+: Extreme UV exposure (damage to skin in <10 minutes).

Water Quality Index

A water quality index (Brown and Froemke 2012) is reported that expresses the overall water quality (0-5; 0 = no risk, 5 = highest risk) at a certain location and time based on several water quality parameters:

- ✿ Water clarity
- ✿ Dissolved oxygen
- ✿ Oxygen demand
- ✿ Nutrients
- ✿ Bacteria

Wildfire Potential

Wildfire hazard potential data were obtained from the USDA Forest Service (2014) Fire, Fuel, Smoke Science Program and are designed to depict the relative potential for wildfire that would be difficult for suppression resources to contain.

Wildland-Urban Interface

The 1990 and 2010 wildland-urban interface (WUI) data were obtained from the University of Wisconsin-Madison Silvis lab (Martinuzzi et al. 2015, Radeloff et al. 2017). Two types of WUI data for 1990 and 2010 are displayed: percent intermix and interface (along with percent non-interface area). Intermix WUI are areas where housing and vegetation intermingle; interface WUI are areas with housing in the vicinity of contiguous wildland vegetation.

Based on all of these local environmental data and estimates of ecosystem services and values, users can weight these layers to determine area of prioritization for management actions.

Prioritization

To determine the best locations to plant or protect trees, tree and impervious cover data are used in conjunction with U.S. Census data and various layers (e.g., areas with highest population density, lowest tree density, or lowest tree cover per capita). i-Tree Landscape creates an index that prioritizes areas among the selected geographic units. The higher the index value, the higher the priority of the area for tree planting or protection. The index is developed with user-determined importance values, or “weights”, assigned to up to three layers. Each layer is weighted between 0 to 100, such that the sum of the layers must equal 100.

















As geographic areas differ in size, all index inputs are either in percentages or standardized per unit area or person. Each layer is standardized on a scale of 0 to 1 with 1 representing the geographic area with the highest priority (e.g., areas with highest population density, lowest tree density, or lowest tree cover per capita).

Although users can select their own weights and prioritization schemes, three common scenarios are given:

- ✿ Population: (default) an index weighted toward areas of *relatively high population density*, low tree cover per capita, and high available planting space.
- ✿ Minorities: an index weighted toward areas of *relatively high minority population density*, low tree cover per capita, and high available planting space.
- ✿ Poverty: an index weighted toward areas of *relatively high proportion of population below the poverty line*, low tree cover per capita, and high available planting space.

Information on methods and where the numerous layers of data (e.g., census data, wildfire data) were obtained is available at the i-Tree Landscape reference web page (i-Tree Team, n.d.).




Planned Future Improvements

-  Add links to local FIA and i-Tree field data.
-  Add more high resolution cover maps.
-  Include more units of analysis:
 -  Different HUC watersheds
 -  300 m resolution data
-  Add additional map layers:
 -  Tree species and wildlife range maps
 -  Forest fragmentation
 -  Tree effects on air temperature
 -  City heat islands
 -  Reduced runoff effects based local event mean concentration data
 -  Potential hurricane threat
 -  Protected lands
 -  Heat islands
 -  I-Tree cool temperature estimates
 -  Climate vulnerability index

MYTREE

MyTree is a mobile smart phone application that allows users to easily quantify the benefits and values of individual trees. MyTree calculations are based on the methods in [i-Tree Design](#).



Planned Improvements

-  Create ability to pin trees to a global map.
-  Create option to calculate past and future (total life-span) benefits of trees.
-  Add optional tree health variables and linking these data with the Nature Conservancy's Healthy Trees Healthy Cities Initiative (Nature Conservancy 2019).

OURTREES

OurTrees allows users to quickly explore the benefits provided by the tree canopy cover across the community. In addition to current benefits, a scorecard estimates plantable space and potential benefits based on a 10 percent increase in canopy cover. OurTrees calculations are based on the methods in i-Tree Landscape.





Planned Improvements

-  Analysis for additional geographies.
-  Expansion of the OurTrees scorecard to include additional tree equity analysis.

I-TREE PLANTING

i-Tree Planting is a tool to estimate the long-term environmental benefits from a tree planting project of numerous trees and species. Its methods are based on methods from i-Tree [Design](#) and the i-Tree [Forecast](#) tool.




Planned Improvements

-  Update species list.
-  Add county subdivisions.
-  Add pollutant monetary values.
-  Improve export capabilities.

I-TREE PROJECTS

i-Tree Projects allows users to visualize plot and community data, as well as access and download field data and results for further analysis. The beta version of i-Tree Projects launches with only one i-Tree Eco project from Baltimore, MD, collected as part of the Baltimore Ecosystem Study (<https://www.caryinstitute.org/science/research-projects/baltimore-ecosystem-study>). Once more projects are added, users will be able to compare data among communities.









Planned Improvements

-  Add more cities.
-  Add ability to compare city results.
-  Add map of known project locations.

I-TREE SPECIES

i-Tree Species is designed to help users select the most appropriate tree species based on the species potential environmental services and geographic area. Users select and rank the importance (0–10) of each environmental service desired from trees. The program then calculates the best tree species based on the user-provided weighting of environmental benefits of tree species at maturity.

Species are selected based on three types of information:

-  Hardiness zone—as determined by state and city.
-  Mature height—user-specified minimum and maximum heights.
-  Environmental factors—ranked from 0 to 10:
 -  Air pollution removal
 -  Air temperature reduction
 -  Ultraviolet radiation reduction
 -  Carbon storage
 -  Pollen allergenicity

- ✿ Building energy conservation
- ✿ Wind reduction
- ✿ Stream flow reduction (storm water management)

i-Tree Species methods are detailed in Nowak (2008).

Planned Improvements

- ✿ Update program with more common species.
- ✿ Estimate species effects over the estimated life span of the species.
- ✿ Estimate benefits estimates for conditions from numerous U.S. cities.
- ✿ Add local species limitations to help limit species list (e.g., soil tolerances).

I-TREE STREETS

i-Tree Streets is a tool designed to assess the benefits and values of street tree populations. This tool uses data from 16 reference cities to interpolate values for other U.S. cities. Due to this reference city approach, which is different from other i-Tree tools, i-Tree Streets' outputs have been integrated within i-Tree Eco and street trees are now analyzed using i-Tree Eco. The Streets tool is no longer supported, but is available as a legacy tool.

The primary reason for integrating Streets within Eco is that the Streets program is limited to 16 cities and all subsequent results are based on results from one of the 16 cities. Thus, local city environmental data are not being used, but rather data from the selected reference city. Conversely, i-Tree Eco results are based on local environmental data. For example, if you are analyzing tree data from San Antonio, TX, your reference environmental data in Streets would be coming from Charlotte, NC; using Eco, your environmental data would be from San Antonio. This integration allows for most of the Streets capabilities to be completed using Eco, but with better, more locally appropriate environmental data.

Detailed methods on how the Streets program assesses ecosystem services and values can be found in McPherson et al. (1999, 2000, 2001, 2002, 2003, 2004, 2006a, 2006b, 2006c, 2007, 2010), Peper et al. (2009, 2010), Maco and McPherson (2003), Vargas et al. (2007a, 2007b, 2008) and i-Tree (2017).

Planned Improvements

- ✿ None. Street trees should now be assessed using i-Tree Eco.

I-TREE WOOD MARKETPLACE

i-Tree Marketplace connects urban wood harvests to users of removed trees for upcycling and waste reduction. Information about logs are captured in the field, uploaded to the Cloud, and displayed to potential users. Potential users can peruse these logs and contact their owners to arrange for their disposition. i-Tree Marketplace is designed to be a simple application accessed via most modern Web browsers. This program is currently a beta prototype.

Planned Improvements

- ✦ Expand pilot test.
- ✦ Track logs from removal to recycled use.
- ✦ Set a means for potential monetary exchange.

ACKNOWLEDGMENTS

I thank the many people who have worked on i-Tree methods, code, and support (see [appendix 1](#)), the **Davey Tree**, and the numerous i-Tree partners for their significant support, financial and otherwise, that helped make i-Tree a global success. With regard to this document, a special thanks goes to Satoshi Hirabayashi, Dan Crane, Scott Maco, Mike Binkley, Alexis Ellis, Bob Hoehn, Robbie Coville, and Una Wiegand for providing additional materials regarding various methods and references documentation. Thanks also to David Barton, Robbie Coville, Dan Crane, Eric Greenfield, Richard Hallett, Krista Heinlen, Jason Henning, Erika Teach, and Al Zelaya for review and comments regarding this document. This document was funded in part by the USDA Forest Service State and Private Forestry Urban and Community Forestry Program.

Special thanks also go to the following groups that helped fund the development of various tools:

- ✿ **American Forests**—helped fund i-Tree Canopy.
- ✿ **California Department of Forestry and Fire Protection and California Urban Forest Council**—helped fund i-Tree Planting.
- ✿ **Northeastern Area Association of State Foresters**—provided substantial funding and input in the development of the original version of Landscape.
- ✿ **USDA Climate Hubs**—helped fund land surface temperatures in i-Tree Landscape.

A special thank you to all the people who have contributed to the success of i-Tree ([appendix 1](#)). Many people have been instrumental in securing funding for i-Tree and overall program support through the years. These people include: Michael Rains, Pat Covey, Karl Warnke, Jim Hubbard, Jan Davis, Lauren Marshall, Dennis May, former Forest Service Chief Tom Tidwell, Phil Rodbell, Robin Morgan, Peggy Castillo, Thomas Schmidt, Elizabeth Larry, Steve Koehn, Lon Yeary, Robert Bridges, Richard Birdsey, Dudley Hartel, and Eric Kuehler. A special thank you also to the many users who had provided advice and input to improve i-Tree.

LITERATURE CITED

Several of the links associated with these citations are no longer working. We have attempted to update as many links as possible. Those updated links have an associated access date of October 2023.

- Abdi, R.; Endreny T. 2019. **A river temperature model to assist managers in identifying thermal pollution causes and solutions.** *Water*. 11(5): 1060. <https://doi.org/10.3390/w11051060>.
- Abdi, R.; Endreny, T.; Nowak, D. 2020. **A model to integrate urban river thermal cooling in river restoration.** *Journal of Environmental Management*. 258: 110023. 9 p. <https://doi.org/10.1016/j.jenvman.2019.110023>.
- ACRT. 1997. **Large tree model technical manual.** Cuyahoga Falls, OH: ACRT, Inc.
- Australian Energy Market Operator. 2010. **Australian energy market operator** <https://www.aemo.com.au/> (accessed 2010).
- Baldocchi, D. 1988. **A multi-layer model for estimating sulfur dioxide deposition to a deciduous oak forest canopy.** *Atmospheric Environment*. 22(5): 869–884. [https://doi.org/10.1016/0004-6981\(88\)90264-8](https://doi.org/10.1016/0004-6981(88)90264-8).
- Baldocchi, D.D.; Hicks, B.B.; Camara, P. 1987. **A canopy stomatal resistance model for gaseous deposition to vegetated surfaces.** *Atmospheric Environment*. 21: 91–101. [https://doi.org/10.1016/0004-6981\(87\)90274-5](https://doi.org/10.1016/0004-6981(87)90274-5).
- Barbour, M.G.; Burk, J.H.; Pitts, W.D. 1980. **Terrestrial plant ecology.** 1st ed. Menlo Park, CA: Benjamin/Cummings. 604 p. ISBN: 978-0805305401.
- Bidwell, R.G.S.; Fraser, D.E. 1972. **Carbon monoxide uptake and metabolism by leaves.** *Canadian Journal of Botany*. 50: 1435–1439. <https://doi.org/10.1139/b72-174>.
- Binder, S.; Haight, R.G.; Polasky, S.; Warziniack, T.; Mockrin, M.H. [et al.]. 2017. **Assessment and valuation of forest ecosystem services: State of the science review.** Gen. Tech. Rep. NRS-170. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 47 p. <https://doi.org/10.2737/NRS-GTR-170>.
- Bird Life International. 2020. **Data zone.** Cambridge, UK: BirdLife International. <http://datazone.birdlife.org/home> (accessed Feb. 2020).
- Brown, T.C.; Froemke, P. 2012. **Nationwide assessment of nonpoint source threats to water quality.** *BioScience*. 62(2): 136–146. <https://doi.org/10.1525/bio.2012.62.2.7>.
- Buckelew-Cumming, A.; Twardus, D.B.; Nowak, D.J. 2008. **Urban forest health monitoring: large scale assessments in the United States.** *Arboriculture and Urban Forestry*. 34(6): 341–346.
- Burns, R.M.; Honkala, B.H., tech. coords. 1990a. **Silvics of North America, conifers.** *Agric. Handb.* 654. Washington, DC: U.S. Department of Agriculture. 675 p. Vol. 1.

- Burns, R.M.; Honkala, B.H., tech. coords. 1990b. **Silvics of North America, hardwoods**. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture. 877 p. Vol. 2.
- Cai, H; Wang, M.; Elgowainy, A.; Han, J. 2012. **Updated greenhouse gas and criteria air pollutant emission factors and their probability distribution functions for electric generating units**. ANL/ESD/12-2. Argonne, IL: U.S. Department of Energy, Argonne National Laboratory. 143 p.
- Cairns, M.A.; Brown, S.; Helmer, E.H.; Baumgardner, G.A. 1997. **Root biomass allocation in the world's upland forests**. *Oecologia*. 111: 1–11. <https://doi.org/10.1007/s004420050201>.
- Charbeneau, R.J.; Barretti, M.E. 1998. **Evaluation of methods for estimating stormwater pollutant loads**. *Water Environment Research*. 70: 1295–1302. <https://doi.org/10.2175/106143098x123679>.
- Chave, J.; Andalo, C.; Brown, S.; Cairns, M.A.; Chambers, J.Q. [et al.]. 2005. **Tree allometry and improved estimation of carbon stocks and balance in tropical forests**. *Oecologia*. 145(1): 87–99. <https://doi.org/10.1007/s00442-005-0100-x>.
- Chave, J.; Coomes, D.; Jansen, S.; Lewis, S.L.; Swenson, N.G.; Zanne, A.E. 2009. **Towards a worldwide wood economics spectrum**. *Ecology Letters*. 12(4): 351–366. <https://doi.org/10.1111/j.1461-0248.2009.01285.x>.
- Chow, P.; Rolfe, G.L. 1989. **Carbon and hydrogen contents of short-rotation biomass of five hardwood species**. *Wood and Fiber Science*. 21(1): 30-36.
- Colbeck, I.; Harrison, R.M. 1985. **Dry deposition of ozone: some measurements of deposition velocity and of vertical profiles to 100 metres**. *Atmospheric Environment*. 19(11): 1807–1818. [https://doi.org/10.1016/0004-6981\(85\)90007-1](https://doi.org/10.1016/0004-6981(85)90007-1).
- Council of Tree and Landscape Appraisers [CTLA]. 1988. **Valuation of landscape trees, shrubs, and other plants**. 7th ed. Savoy, IL: International Society of Arboriculture.
- Council of Tree and Landscape Appraisers [CTLA]. 1992. **Guide for plant appraisal**. Savoy, IL: International Society of Arboriculture. 103 p.
- Coville, R.; Endreny, T.; Nowak, D.J. 2019. **Chapter 19: Modeling the impact of urban trees on hydrology**. In: Levia, D.F.; Carlyle-Moses, D.E.; Iida, S.; Michalzik, B.; Nanko, K.; Tischer, A., eds. *Forest-water interactions*. Ecological Studies (Analysis and Synthesis), vol. 240. Berlin, Germany: Springer: 459–487. https://doi.org/10.1007/978-3-030-26086-6_19.
- Crow, T. 1980. **A rainforest chronicle: a 30-year record of change in structure and composition at El Verde, Puerto Rico**. *Biotropica*. 12(1): 42–55. <https://doi.org/10.2307/2387772>.
- Da Silva, F.; Suwa, R.; Kajimoto, T.; Ishizuka, M.; Higuchi, N.; Kunert, N. 2015. **Allometric equations for estimating biomass of *Euterpe precatoria*, the most abundant palm species in the Amazon**. *Forests*. 6: 450–463. <https://doi.org/10.3390/f6020450>.
- Daly, C.; Widrlechner, M.P.; Halbleib, M.D.; Smith, J.I.; Gibson, W.P. 2012. **Development of a new USDA Plant Hardiness Zone map for the United States**. *Journal of Applied Meteorology and Climatology*. 51(2): 242–264. <https://doi.org/10.1175/2010jamc2536.1>.

- Deardorff, J.W. 1978. **Efficient prediction of ground surface temperature and moisture with inclusion of a layer of vegetation.** Journal of Geophysics Research. 83(C4): 1899–1903. <https://doi.org/10.1029/jc083ic04p01889>.
- Deru, M.; Torcellini, P. 2007. **Source energy and emission factors for energy use in buildings.** Tech. Rep. NREL/TP-550-38617. Golden, CO: U.S. Department of Energy, National Renewable Energy Lab. 39 p. <https://www.nrel.gov/docs/fy07osti/38617.pdf> (accessed May 7, 2019).
- deVries, R.E. 1987. **A preliminary investigation of the growth and longevity of trees in Central Park.** New Brunswick, NJ: Rutgers University. 95 p. M.S. thesis.
- Driscoll, C.T.; Lambert, K.F.; Chapin, F.S.; Hart, C.; Nowak, D.J. [et al.]. 2012. **Science and society: The role of long-term studies in environmental stewardship.** BioScience. 62(4): 354–366. <https://doi.org/10.1525/bio.2012.62.4.7>.
- Driver, N.E.; Mustard, M.H.; Rhinesmith, R.B.; Middelburg, R.F. 1985. **U.S. Geological Survey urban-stormwater data base for 22 metropolitan areas throughout the United States.** Open-File Report 85-337. Lakewood, CO: U.S. Department of Interior, Geological Survey. 219 p. <https://doi.org/10.3133/ofr85337>.
- Ellenwood, J.R.; Krist, F.J.; Romero, S.A. 2015. **Species parameter maps [datasets].** In: National individual tree species atlas. FHTET-15-01. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team. <https://www.fs.usda.gov/foresthealth/applied-sciences/mapping-reporting/indiv-tree-parameter-maps.shtml> (accessed Oct. 2023).
- Energy Solutions. 2014. **Energy solutions.** <https://www.energybrokers.co.uk/> (accessed 2014).
- Eurostat. 2019. **Your key to European statistics.** <https://ec.europa.eu/eurostat> (accessed 2019).
- Exfor. 2014. **Exfor database.** <https://www.landcan.org/pdfs/guidelines.pdf> (accessed January 2020).
- Fleming, L.E. 1988. **Growth estimation of street trees in central New Jersey.** New Brunswick, NJ: Rutgers University. 143 p. M.S. thesis.
- Frelich, L.E. 1992. **Predicting dimensional relationships for Twin Cities shade trees.** St. Paul, MN: University of Minnesota, Department of Forest Resources. 33 p.
- Geron, C.D.; Guenther, A.B.; Pierce, T.E. 1994. **An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States.** Journal of Geophysical Research. 99(D6): 12,773–12,791. <https://doi.org/10.1029/94jd00246>.
- Gleason, H.A.; Cronquist, A. 1991. **Manual of vascular plants of northeastern United States and adjacent Canada.** Bronx, NY: New York Botanical Garden. 910 p. ISBN: 978-0893273651.
- GlobAllomeTree. 2017. **GlobAllomeTree, assessing volume, biomass and carbon stocks of trees and forests.** <http://www.globallometree.org/accounts/login/> (accessed Dec. 2017).

- Goodman, R.C.; Phillips, O.L.; del Castillo Torres, D.; Freitas, L.; Cortese, S.T. [et al.]. 2013. **Amazon palm biomass and allometry**. *Forest Ecology and Management* 310: 994–1004. <https://doi.org/10.1016/j.foreco.2013.09.045>.
- Grant, R.H.; Heisler, G.M. 2006. **Effect of cloud cover on UVB exposure under tree canopies: will climate change affect UVB exposure?** *Photochemistry and Photobiology*. 82(2): 487–494. <https://doi.org/10.1562/2005-07-07-ra-604> (accessed Jan. 2020).
- Grant, R.H.; Heisler, G.M.; Gao, W. 2002. **Estimation of pedestrian level UV exposure under trees**. *Photochemistry and Photobiology*. 75(4): 369–376. [https://doi.org/10.1562/0031-8655\(2002\)0750369EOPLUE2.0.CO2](https://doi.org/10.1562/0031-8655(2002)0750369EOPLUE2.0.CO2).
- Grimm, W.C. 1962. **The book of trees. 2nd edition**. Harrisburg, PA: Stackpole Co. 487 p.
- Guenther, A. 1997. **Seasonal and spatial variation in natural volatile organic compound emissions**. *Ecological Applications*. 7(1): 34–45. <https://doi.org/10.2307/2269405>.
- Guenther, A.; Hewitt, C.N.; Erickson, D.; Fall, R.; Geron, C. [et al.]. 1995. **A global model of natural volatile organic compound emissions**. *Journal of Geophysical Research*. 100 (D5): 8873–8892. <https://doi.org/10.1029/94JD02950>.
- Heisler, G.M.; Grant, R.H.; Gao, W. 2003a. **Individual- and scattered-tree influences on ultraviolet irradiance**. *Agricultural and Forest Meteorology*. 120(1–4): 113–126. <https://doi.org/10.1016/j.agrformet.2003.08.024>.
- Heisler, G.M.; Grant, R.H.; Nowak, D.J.; Gao, W.; Crane, D.E.; Walton, J.T. 2003b. **Inclusion of an ultraviolet radiation transfer component in an urban forest effects model for predicting tree influences on potential below-canopy exposure to UVB radiation**. In: Slusser, J.R.; Herman, J.R.; Gao, W., eds. *Proceedings of SPIE, Ultraviolet ground- and space-based measurements, models, and effects III; 2003 August 4–6; San Diego, CA*. Bellingham, WA: SPIE: 228–235.
- Hirabayashi, S. 2012. **i-Tree Eco biogenic emissions model descriptions**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. 8 p. http://www.itreetools.org/eco/resources/iTree_Eco_Biogenic_Emission_Model_Descriptions_V1.0.pdf (accessed Dec. 2017).
- Hirabayashi, S. 2013. **i-Tree Eco precipitation interception model descriptions**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. 21 p. https://www.itreetools.org/eco/resources/iTree_Eco_Precipitation_Interception_Model_Descriptions.pdf (accessed Dec. 2017).
- Hirabayashi, S. 2015. **i-Tree Eco United States county-based hydrologic estimates**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. http://www.itreetools.org/landscape/resources/Eco_US_county-based_hydrologic_estimates.pdf (accessed Jan. 2020).
- Hirabayashi, S. 2016. **Air pollutant removals, biogenic emissions and hydrologic estimates for i-Tree applications**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. 57 p. https://www.itreetools.org/landscape/resources/Air_Pollutant_Removals_Biogenic_Emissions_and_Hydrologic_Estimates_for_iTree_v6_Applications.pdf (accessed Dec. 2017).

- Hirabayashi, S. 2017. **Weather station data quality assessment**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. http://www.itreetools.org/eco/resources/v6/Eco_v6_weather_station_validation_description.pdf (accessed Dec. 2017).
- Hirabayashi, S.; Endreny, T.N. 2016. **Surface and upper weather pre-processor for i-Tree Eco and Hydro**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. 19 p. https://www.itreetools.org/eco/resources/Surface_weather_and_upper_air_preprocessor_description.pdf (accessed Dec. 2017).
- Hirabayashi, S.; Kroll, C.N. 2017. **Single imputation method of missing air quality data for i-Tree Eco analyses in the conterminous United States**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. 24 p. http://www.itreetools.org/eco/resources/Single_imputation_method_of_missing_air_quality_data_for_i-Tree_Eco_analyses_in_the_conterminous_United_States.pdf (accessed Dec. 2017).
- Hirabayashi, S.; Kroll C.N.; Nowak, D.J. 2011. **Component-based development and sensitivity analyses of an air pollutant dry deposition model**. Environmental Modeling and Software. 26: 804–816. <https://doi.org/10.1016/j.envsoft.2010.11.007>.
- Hirabayashi, S.; Kroll, C.N.; Nowak, D.J. 2015. **i-Tree Eco dry deposition model descriptions**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. https://www.itreetools.org/documents/60/i-Tree_Eco_Dry_Deposition_Model_Descriptions_V1.5.pdf (accessed Oct. 2023).
- Hirabayashi, S.; Nowak, D.J. 2016. **Comprehensive national database of tree effects on air quality and human health in the United States**. Environmental Pollution. 215: 48–57. <https://doi.org/10.1016/j.envpol.2016.04.068>.
- Hodges, J.L.; Lehmann, E.L. 1964. **Basic concepts of probability and statistics**. 1st ed. San Francisco, CA: Holden-Day. 375 p.
- Homer, C.G.; Dewitz, J.A.; Yang, L.; Jin, S.; Danielson, P. [et al.]. 2015. **Completion of the 2011 National Land Cover Database for the conterminous United States—Representing a decade of land cover change information**. Photogrammetric Engineering and Remote Sensing. 81(5): 345–354. <https://doi.org/10.14358/PERS.81.5.345>.
- Hosker, R.P.; Lindberg, S.E. 1982. **Review: atmospheric deposition and plant assimilation of gases and particles**. Atmospheric Environment. 16(5): 889–910.
- Hough, R.B. 1907. **Handbook of the trees of the northern states and Canada**. Lowville, NY: R.B. Hough. 470 p.
- Inhabit.earth. No date. **Community food forestry initiative**. Miami, FL: [formerly] Earth Learning, Inc. <http://inhabit.earth/community-food-forestry/> (accessed Feb. 2020).
- Interagency Working Group on Social Cost of Carbon. 2016. **Technical support document: Social cost of carbon for regulatory impact analysis under Executive Order 12866**. https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf (accessed December 2019).

- International Energy Agency. 2018 **Find out about a fuel, a technology or a sector**. <https://www.iea.org/> (accessed 2018).
- i-Tree Team. 2017. **i-Tree streets & STRATUM resources**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. <https://www.itreetools.org/resources/archives.php> (accessed Dec. 2017).
- i-Tree Team. 2019a. **i-Tree Eco field manual. Ver. 6.0 (7.2.2019)**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. <https://www.itreetools.org/support/resources-overview/i-tree-manuals-workbooks> (accessed Jan. 2020).
- i-Tree Team. 2019b. **i-Tree Eco guide to international projects**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. https://www.itreetools.org/resources/manuals/Ecov6_ManualsGuides/Ecov6Guide_InternationalProjects.pdf (accessed Feb. 2020).
- i-Tree Team. 2019c. **i-Tree Eco user's manual, Ver. 6.0 (7.2.2019)**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. <https://www.itreetools.org/support/resources-overview/i-tree-manuals-workbooks> (accessed Jan. 2020).
- i-Tree Team. No date. **i-Tree Landscape references**. Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. <https://landscape.itreetools.org/references/> (accessed Feb. 2020).
- Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. 2003. **National-scale biomass estimators for United States tree species**. *Forest Science*. 49(1): 12–35.
- Killus, J.P.; Meyer, J.P.; Durran, D.R.; Anderson, G.E.; Jerskey, T.N. [et al.]. 1984. **Continued research in mesoscale air pollution simulation modeling**. Volume V: refinements in numerical analysis, transport, chemistry, and pollutant removal. Publ. EPA/600/3-84/095a. Research Triangle Park, NC: U.S. Environmental Protection Agency.
- Kinnee, E.; Geron, C.; Pierce, T. 1997. **United States land use inventory for estimating biogenic ozone precursor emissions**. *Ecological Applications*. 7(1): 46–58. <https://doi.org/10.2307/2269406>.
- Korzhenevych, A.; Dehnen, N.; Bocker, J.; Holtcamp, M.; Meier, H. [et al.]. 2014. **Update of the handbook on external costs of transportation**. Report for the European Commission. ED57769 Number 1. London, UK: Ricardo-AEA. 139 p. https://ec.europa.eu/transport/sites/transport/files/handbook_on_external_costs_of_transport_2014_0.pdf (accessed May 7, 2019).
- Leonardo Academy. 2011. **Leonardo Academy's guide to calculating emissions including emission factors and energy prices**. Madison, WI: Leonardo Academy. 26 p. http://www.cleanerandgreener.org/download/2010-06-14%20Leonardo%20Academy%20C&G%20Emission%20Factors%20and%20Energy%20Prices_LEO%20format.pdf (accessed March 16, 2020).

- Lerman, S.B; Nislow, K.H.; Nowak, D.J.; DeStefano, S.; King, D.I.; Jones-Farrand, D.T. 2014. **Using urban forest assessment tools to model bird habitat potential.** Landscape and Urban Planning. 122: 29–40. <https://doi.org/10.1016/j.landurbplan.2013.10.006>.
- Liebholt, A. 2010. **Geographical distribution of forest pest species in US.** Unpublished draft manuscript submitted to Frontiers in Ecology and the Environment.
- Lindgren, B.W.; McElrath, G.W. 1969. **Introduction to probability and statistics.** London, U.K.: Macmillan.
- Lindsey, R. 2022. **Interactive map: average date of last spring freeze across the United States.** Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration. <https://www.climate.gov/news-features/understanding-climate/interactive-map-average-date-last-spring-freeze-across-united> (accessed Oct. 2023).
- Little, E.L., Jr. 1971. **Atlas of United States trees. Conifers and important hardwoods.** Misc. Pub. 1146. Washington, DC: U.S. Department of Agriculture, Forest Service. 400 p. Vol. 1.
- Little, E.L., Jr. 1976. **Atlas of United States trees. Minor western hardwoods.** Misc. Pub. 1314. Washington, DC: U.S. Department of Agriculture, Forest Service. 300 p. Vol. 3.
- Little, E.L., Jr. 1977. **Atlas of United States trees. Minor eastern hardwoods.** Misc. Pub. 1342. Washington, DC: U.S. Department of Agriculture, Forest Service. 235 p. Vol. 4.
- Little, E.L., Jr. 1978. **Atlas of United States trees. Florida.** Misc. Pub. 1361. Washington, DC: U.S. Department of Agriculture, Forest Service. 138 p. Vol. 5.
- Lovett, G.M. 1994. **Atmospheric deposition of nutrients and pollutants in North America: an ecological perspective.** Ecological Applications. 4(4): 629–650. <https://doi.org/10.2307/1941997>.
- Maco, S.E.; McPherson, E.G. 2003. **A practical approach to assessing structure, function, and value of street tree populations in small communities.** Journal of Arboriculture. 29(2): 84–92.
- Magurran, A.E. 1988. **Ecological diversity and its measurement.** Princeton, NJ: Princeton University Press. 179 p. ISBN-13: 978-0691084916.
- Marten, A.L.; Newbold, S.C. 2011. **Estimating the social cost of non-CO2 GHG emissions: methane and nitrous oxide.** Working Paper 11-01. Washington, DC: U.S. Environmental Protection Agency, National Center for Environmental Economics. 31 p. <https://www.epa.gov/environmental-economics/working-paper-estimating-social-cost-non-co2-ghg-emissions-methane-and> (accessed May 7, 2019).
- Martinuzzi, S.; Stewart, S.I.; Helmers, D.P.; Mockrin, M.H.; Hammer, R.B.; Radeloff, V.C. 2015. **The 2010 wildland-urban interface of the conterminous United States.** Res. Map NRS-8. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 124 p. <https://doi.org/10.2737/NRS-RMAP-8>.
- Matthews, S.N.; Iverson, L.R.; Peters, M.P.; Prasad A. 2018. **Assessing potential climate change pressures across the conterminous United States: mapping plant hardiness**

- zones, heat zones, growing degree days, and cumulative drought severity throughout this century.** Res. Map NRS-9. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 31 p. <https://doi.org/10.2737/NRS-RMAP-9>.
- Matthews, S.N.; Iverson, L.R.; Peters, M.P.; Prasad, A.M. 2019. **Climate change pressures for the conterminous United States: plant hardiness zones, heat zones, growing degree days, and cumulative drought severity.** Fort Collins, CO: Forest Service Research Data Archive. <https://doi.org/10.2737/RDS-2019-0001>.
- Maxwell, E.L. 1994. **A meteorological/statistical solar radiation model.** In: Proceedings of the 1994 annual conference of the American Solar Energy Society. San Jose, CA: American Solar Energy Society: 421–426.
- McHale, M.R.; Burke, I.C.; Lefsky, M.A.; Peper, P.J.; McPherson, E.G. 2009. **Urban forest biomass estimates: is it important to use allometric relationships developed specifically for urban trees?** *Urban Ecosystems*. 12: 95–113. <https://doi.org/10.1007/s11252-009-0081-3>.
- McPherson, E.G., ed. 1984. **Energy-conserving site design.** Washington, DC: Landscape Architecture Foundation. 325 p.
- McPherson, E.G.; Maco, S.E.; Simpson, J.R.; Peper, P.J.; Xiao, Q. [et al.]. 2002. **Western Washington and Oregon community tree guide: Benefits, costs, and strategic planting.** Silverton, OR: International Society of Arboriculture, Pacific Northwest Chapter. 58 p.
- McPherson, E.G.; Nowak, D.J.; Rowntree, R.A., eds. 1994. **Chicago's urban forest ecosystem: results of the Chicago Urban Forest Ecosystem Project.** Gen. Tech. Rep. NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 201 p. <https://doi.org/10.2737/NE-GTR-186>.
- McPherson, E.G.; Simpson, J.R. 1999. **Carbon dioxide reduction through urban forestry: Guidelines for professional and volunteer tree planters.** Gen. Tech. Rep. PSW-171. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 237 p. <https://doi.org/10.2737/PSW-GTR-171>.
- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Gardner, S.L.; Crowell, A.M.N.; Xiao, Q. 2010. **Northern California coast community tree guide: benefits, costs, and strategic planting.** Gen. Tech. Rep. PSW-GTR-228. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 118 p. <https://doi.org/10.2737/PSW-GTR-228>.
- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Gardner, S.L.; Vargas, K.E. [et al.]. 2006a. **Coastal plain community tree guide: Benefits, costs, and strategic planting.** Gen. Tech. Rep. PSW-GTR-201. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research. 105 p. <https://doi.org/10.2737/PSW-GTR-201>.
- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Gardner, S.L.; Vargas, K.E.; Xiao, Q. 2007. **Northeast community tree guide: benefits, costs, and strategic planting.** Gen. Tech. Rep. PSW-GTR-202. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research. 106 p. <https://doi.org/10.2737/PSW-GTR-202>.

- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Maco, S.E.; Gardner, S.L. [et al.]. 2006b. **Midwest community tree guide: Benefits, costs and strategic planting**. Gen. Tech. Rep. PSW-GTR-199. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research. 85 p. <https://doi.org/10.2737/PSW-GTR-199>.
- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Maco, S.E.; Gardner, S.L. [et al.]. 2006c. **Piedmont community tree guide: Benefits, costs, and strategic planting**. Gen. Tech. Rep. PSW-GTR-200. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research. 99 p. <https://doi.org/10.2737/PSW-GTR-200>.
- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Maco, S.E.; Xiao, Q.; Mulrean, E. 2004. **Desert southwest community tree guide: Benefits, costs and strategic planting**. Phoenix, AZ: Arizona Community Tree Council. 76 p.
- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Scott, K.I.; Xiao, Q. 2000. **Tree guidelines for coastal southern California communities**. Sacramento, CA: Local Government Commission. 97 p. https://www.itreetools.org/streets/resources/Streets_CTG/CUFR_48_Southern_California_Coast_CTG.pdf (accessed May 7, 2019).
- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Xiao, Q. 1999. **Tree guidelines for San Joaquin Valley communities**. Sacramento, CA: Local Government Commission. 64 p.
- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Xiao, Q.; Maco, S.E.; Hoefler, P.J. 2003. **Northern mountain and prairie community tree guide: Benefits, costs and strategic planting**. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 88 p.
- McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Xiao, Q.; Pittenger, D.R.; Hodel, D.R. 2001. **Tree guidelines for Inland Empire Communities**. Sacramento, CA: Local Government Commission. 116 p.
- McPherson, E.G.; van Doorn, N.S.; Peper, P.J. 2016. **Urban tree database and allometric equations**. Gen. Tech. Rep. PSW-GTR-235. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 86 p. <https://doi.org/10.2737/PSW-GTR-235>.
- McPherson, E.G.; Xiao, Q.; van Doorn, N.S.; Johnson, N.; Albers, S.; Peper, P.J. 2018. **Shade factors for 149 taxa of in-leaf urban trees in the USA**. *Urban Forestry & Urban Greening*. 31: 204–211. <https://doi.org/10.1016/j.ufug.2018.03.001>.
- Monteith, J.L.; Unsworth, M.H. 1990. **Principles of environmental physics**. 2nd ed. New York, NY: Edward Arnold. 291 p.
- Morani, A.; Nowak, D.; Hirabayashi, S.; Guidolotti, G.; Medori, M. [et al.]. 2014. **Comparing modeled ozone deposition with field measurements in a periurban Mediterranean forest**. *Environmental Pollution*. 195: 202-209. <https://doi.org/10.1016/j.envpol.2014.08.031>.
- Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingne, R.L.; Harmel, R.D.; Veith, T.L. 2007. **Model evaluation guidelines for systematic quantification of accuracy in watershed**

- simulations.** American Society of Agricultural and Biological Engineers. 50(3): 885-900. <https://doi.org/10.13031/2013.23153>.
- Murray, F.J.; Marsh, L.; Bradford, P.A. 1994. **New York State energy plan, vol. II: Issue reports.** Albany, NY: New York State Energy Office.
- Na, H.R.; Heisler, G.M.; Nowak, D.J.; Grant, R.H. 2014. **Modeling of urban trees' effects on reducing human exposure to UV radiation in Seoul, Korea.** Urban Forestry and Urban Greening. 13(4): 785–792. <https://doi.org/10.1016/j.ufug.2014.05.009>.
- National Atlas of the United States. 2014. **1:1,000,000-scale federal lands of the United States.** https://nationalmap.gov/small_scale/atlasftp.html (accessed June 2018).
- National Center for Atmospheric Research. 2016. **Community climate system model.** Boulder, CO: National Center for Atmospheric Research. <http://www.cesm.ucar.edu/models/ccsm3.0/> (accessed June 2016).
- National Oceanic and Atmospheric Administration [NOAA]. 2017. **Sea level rise inundation.** Charleston, SC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office for Coastal Management. <https://coast.noaa.gov/slrdata> (accessed June 2019).
- Natural Resources Canada. 2012. **Energy facts.** <https://www.nrcan.gc.ca> (accessed July 2012).
- Nature Conservancy. 2019. **Healthy trees healthy cities initiative.** <https://www.conservationgateway.org/ConservationPractices/cities/hthc/Pages/default.aspx> (accessed July 20, 2019).
- Nelson, R.K.; LaDale Winling, L.; Marciano, R.; Connolly, N. [et al.]. **Mapping inequality.** In: Nelson, R.K.; Ayers, E.L., eds. American panorama. Richmond, VA: University of Richmond, Digital Scholarship Lab. <https://dsl.richmond.edu/panorama/redlining/> (accessed Oct. 2020).
- Noilhan, J.; Planton, S. 1989. **A simple parameterization of land surface processes for meteorological models.** Monthly Weather Review. 117: 536.
- North Carolina State University. 2018. **Version 5. ForeCASTS Project: Forecasts of climate-associated shifts in tree species.** Raleigh, NC: North Carolina State University. <https://www.geobabble.org/ForeCASTS/atlas.html> (accessed June 2018).
- Nowak, D.J. 1986. **Silvics of an urban tree species: Norway maple (*Acer platanoides* L.).** Syracuse, NY: State University of New York, College of Environmental Science and Forestry. 148 p. M.S. thesis.
- Nowak, D.J. 1991. **Urban forest development and structure: analysis of Oakland, California.** Berkeley, CA: University of California. 232 p. Ph.D. dissertation.
- Nowak, D.J. 1993. **Atmospheric carbon reduction by urban trees.** Journal of Environmental Management. 37(3): 207–217. <https://doi.org/10.1006/jema.1993.1017>.
- Nowak, D.J. 1994a. **Air pollution removal by Chicago's urban forest.** In: McPherson, E.G; Nowak, D.J.; Rowntree, R.A., eds. Chicago's urban forest ecosystem: Results of the Chicago

- Urban Forest Climate Project. Gen. Tech. Rep. NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 63–81.
- Nowak, D.J. 1994b. **Atmospheric carbon dioxide reduction by Chicago's urban forest.** In: McPherson, E.G; Nowak, D.J.; Rowntree, R.A., eds. Chicago's urban forest ecosystem: Results of the Chicago Urban Forest Climate Project. Gen. Tech. Rep. NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 83–94.
- Nowak, D.J. 1994c. **Urban forest structure: the state of Chicago's urban forest.** In: McPherson, E.G; Nowak, D.J.; Rowntree, R.A., eds. Chicago's urban forest ecosystem: Results of the Chicago Urban Forest Climate Project. Gen. Tech. Rep. NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 3–18 and 140–164.
- Nowak, D.J. 1996. **Estimating leaf area and leaf biomass of open-grown urban deciduous trees.** *Forest Science*. 42(4): 504–507.
- Nowak, D.J. 2005. **UFORE methods.** Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. <https://www.itreetools.org/eco/resources/UFORE%20Methods.pdf> (accessed Dec. 2017).
- Nowak, D.J. 2008. **Species selector application.** Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. <http://www.itreetools.org/species/resources/SpeciesSelectorMethod.pdf> (accessed Dec. 2017).
- Nowak, D.J. 2011. **i-Tree canopy technical notes.** Washington, DC: U.S. Department of Agriculture, Forest Service; Kent, OH: Davey Tree Expert Co.; and other cooperators. <https://help.itreetools.org/canopy/references?embed=true> (accessed Oct. 2023).
- Nowak, D.J. 2018. **Quantifying and valuing the role of trees and forests on environmental quality and human health.** In: van den Bosch, M.; Bird, W., eds. Nature and public health. Oxford textbook of nature and public health. Oxford, UK: Oxford University Press: 312–316. Chapter 10.4.
- Nowak, D.J.; Bodine, A.R.; Hoehn, R.E.; Edgar, C.B.; Hartel, D.R. [et al.]. 2016. **Austin's urban forest, 2014.** Resour. Bull. NRS-100. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station 55 p. <https://doi.org/10.2737/NRS-RB-100>.
- Nowak, D.J.; Bodine, A.R.; Hoehn, R.E.; Edgar, C.B.; Riley, G. [et al.]. 2017. **Houston's urban forest, 2015.** Resour. Bull. SRS-211. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 91 p. <https://doi.org/10.2737/SRS-RB-211>.
- Nowak, D.J.; Buckelew-Cumming, A.; Twardus, D.; Hoehn, R.; Mielke, M. 2007a. **National Forest Health Monitoring Program, monitoring urban forests in Indiana: Pilot study 2002, Part 2: Statewide estimates using the UFORE model.** NA-FR-01-07. Morgantown, WV: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry. 13 p.

- Nowak, D.J.; Civerolo, K.L.; Rao, S.T.; Sistla, G.; Luley, C.J.; Crane, D.E. 2000. **A modeling study of the impact of urban trees on ozone.** Atmospheric Environment. 34(10): 1601–1613. <https://doi.org/10.3390/atmos10030154>.
- Nowak, D.J.; Crane, D.E. 2002. **Carbon storage and sequestration by urban trees in the USA.** Environmental Pollution. 116(3): 381–389. [https://doi.org/10.1016/s0269-7491\(01\)00214-7](https://doi.org/10.1016/s0269-7491(01)00214-7).
- Nowak, D.J.; Crane, D.E.; Dwyer, J.F. 2002a. **Compensatory value of urban trees in the United States.** Journal of Arboriculture. 28(4): 194–199.
- Nowak, D.J.; Crane, D.E.; Stevens, J.C.; Hoehn, R.E.; Walton, J.T. 2008. **A ground-based method of assessing urban forest structure and ecosystem services.** Arboriculture & Urban Forestry. 34(6): 347–358.
- Nowak, D.J.; Crane, D.E.; Stevens, J.C.; Ibarra, M. 2002b. **Brooklyn’s Urban Forest.** Gen. Tech. Rep. NE-290. Newtown Square, PA. U.S. Department of Agriculture, Forest Service, Northeastern Research Station 107 p. <https://doi.org/10.2737/NE-GTR-290>.
- Nowak, D.J.; Cumming, A.; Twardus, D.; Hoehn, R.E.; Brandeis, T.J.; Oswalt, C.M. 2012. **Urban forests of Tennessee.** Gen. Tech. Rep. SRS-149. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 52 p. <https://doi.org/10.2737/SRS-GTR-149>.
- Nowak, D.J.; Greenfield, E.J. 2010. **Evaluating the National Land Cover Database tree canopy and impervious cover estimates across the conterminous United States: A comparison with photo-interpreted estimates.** Environmental Management. 46: 378–390.
- Nowak, D.J.; Greenfield, E.J. 2012. **Tree and impervious cover in the United States.** Landscape and Urban Planning. 107: 21–30. <https://doi.org/10.1016/j.landurbplan.2012.04.005>.
- Nowak, D.J.; Greenfield, E.J. 2018. **US urban forest statistics, values, and projections.** Journal of Forestry. 116(2): 164–177. <https://doi.org/10.1093/jofore/fvx004>.
- Nowak, D.J.; Greenfield, E.J.; Ash, R.M. 2019. **Annual biomass loss and potential value of urban tree waste in the United States.** Urban Forestry & Urban Greening. 46: 126469. 9 p. <https://doi.org/10.1016/j.ufug.2019.126469>.
- Nowak, D.J.; Greenfield, E.J.; Hoehn, R.; LaPoint, E. 2013a. **Carbon storage and sequestration by trees in urban and community areas of the United States.** Environmental Pollution. 178: 229–236. <https://doi.org/10.1016/j.envpol.2013.03.019>.
- Nowak, D.J.; Hirabayshi S.; Bodine, A.; Hoehn, R. 2013b. **Modeled PM_{2.5} removal by trees in ten U.S. cities and associated health effects.** Environmental Pollution. 178: 395–402. <https://doi.org/10.1016/j.envpol.2013.03.050>.
- Nowak, D.J.; Hirabayshi S.; Ellis, E.; Greenfield, E. 2014. **Tree and forest effects on air quality and human health in the United States.** Environmental Pollution 193: 119–129. <https://doi.org/10.1016/j.envpol.2014.05.028>.

- Nowak, D.J.; Hoehn, R.H.; Crane, D.E. 2007b. **Oxygen production by urban trees in the United States.** *Arboriculture and Urban Forestry*. 33(3): 220–226. <https://doi.org/10.48044/jauf.2007.026>.
- Nowak, D.J.; McHale, P.J.; Ibarra, M.; Crane, D.; Stevens, J.; Luley, C. 1998. **Modeling the effects of urban vegetation on air pollution.** In: Gryning, S.E.; Chaumerliac, N., eds. *Air pollution modeling and its application*, XII. New York, NY: Plenum Press: 399–407.
- Nowak, D.J.; Ogren, T.L. 2021. **Variations in urban forest allergy potential among cities and land uses.** *Urban Forestry and Urban Greening*. 63: 127224. <https://doi.org/10.1016/j.ufug.2021.127224>.
- Ottinger, R.L.; Wooley, D.R.; Robinson, N.A.; Hodas, D.R.; Babb, S.E. [et al.]. 1990. **Environmental costs of electricity.** White Plains, NY: Oceana Publications. 769 p. ISBN-13: 978-0379111798.
- Pederson, J.R.; Massman, W.J.; Mahrt, L.; Delany, A.; Oncley, S. [et al.]. 1995. **California ozone deposition experiment: methods, results, and opportunities.** *Atmospheric Environment*. 29(21): 3115–3132. [https://doi.org/10.1016/1352-2310\(95\)00136-m](https://doi.org/10.1016/1352-2310(95)00136-m).
- Peters, M.P.; Iverson, L.R.; Matthews, S.N. 2014. **Spatio-temporal trends of drought by forest type in the conterminous United States, 1960–2013.** Res. Map NRS-7. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. <https://doi.org/10.2737/NRS-RMAP-7>.
- Peper, P.J.; McPherson, E.G. 1998. **Comparison of five methods for estimating leaf area index of opengrown deciduous trees.** *Journal of Arboriculture*. 24(2): 98–111. <https://doi.org/10.48044/jauf.1998.013>.
- Peper, P.J.; McPherson, E.G. 2003. **Evaluation of four methods for estimating leaf area of isolated trees.** *Urban Forestry and Urban Greening*. 2(1): 19-29. <https://doi.org/10.1078/1618-8667-00020>.
- Peper, P.J.; McPherson, E.G.; Simpson, J.R.; Albers, S.N.; Xiao, Q. 2010. **Central Florida community tree guide: benefits, costs, and strategic planting.** Gen. Tech. Rep. PSW-GTR-230. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 118 p. <https://doi.org/10.2737/PSW-GTR-230>.
- Peper, P.J.; McPherson, E.G.; Simpson, J.R.; Vargas, K.E.; Xiao, Q. 2009. **Lower midwest community tree guide: benefits, costs, and strategic planting.** Gen. Tech. Rep. PSW-GTR-219. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 115 p. <https://doi.org/10.2737/PSW-GTR-219>.
- Platt, R. 1968. **Discover American trees.** New York, NY: Dodd, Mead and Co. 256 p. ISBN: [9780396057802](https://doi.org/10.2737/PSW-GTR-219).
- Preston, R.J. 1976. **North American trees.** Ames, IA: Iowa State University Press. 399 p.
- Radeloff, V.C.; Helmers, D.P.; Kramer, H.A.; Mockrin, M.H.; Alexandre, P.M. [et al.]. 2017. **The 1990–2010 wildland-urban interface of the conterminous United States - geospatial data.** 2nd ed. Fort Collins, CO: Forest Service Research Data Archive. <https://doi.org/10.2737/RDS-2015-0012-2>.

- Sanquetta, C.R.; PéllicoNetto, S.; Dalla Corte, A.P.; Rodrigues, A.L.; Behling, A.; Sanquetta, M.N.I. 2015. **Quantifying biomass and carbon stocks in oil palm (*Elaeis guineensis* Jacq.) in northeastern Brazil.** African Journal of Agricultural Research. 10(43): 4067–4075. <https://doi.org/10.5897/ajar2015.9582>.
- Sansalone J.J.; Buchberger, S.G. 1997. **Partitioning and first flush of metals in urban roadway storm water.** Journal of Environmental Engineering. 123(2): 134–143. [https://doi.org/10.1061/\(asce\)0733-9372\(1997\)123:2\(134\)](https://doi.org/10.1061/(asce)0733-9372(1997)123:2(134)).
- Shuttleworth, J.W. 1993. **Evaporation.** In: Maidment, D.R., ed. Handbook of hydrology. New York, NY: McGraw-Hill: 5.1–5.51.
- Singh, S.L.; Sahoo, U.K.; Kenye, A.; Gopoi, A. 2018. **Assessment of growth, carbon stock and sequestration potential of oil palm plantations in Mizoram, northeast India.** Journal of Environmental Protection. 9: 912–931. <https://doi.org/10.4236/jep.2018.99057>.
- Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. 2006. **Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States.** Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p. <https://doi.org/10.2737/NE-GTR-343>.
- Smith, W.B.; Shifley, S.R. 1984. **Diameter growth, survival, and volume estimates for trees in Indiana and Illinois.** Res. Pap. NC-257. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 10 p.
- Smullen, J.T.; Shallcross, A.L.; Cave, K.A. 1999. **Updating the U.S. nationwide urban runoff quality database.** Water Science Technology. 39(12): 9–16. [https://doi.org/10.1016/s0273-1223\(99\)00312-1](https://doi.org/10.1016/s0273-1223(99)00312-1).
- Sobrino, J.A.; Raissouni, N.; Li, Z.L. 2001. **A comparative study of land surface emissivity retrieval from NOAA data.** Remote Sensing of Environment. 75(2): 256–266. [https://doi.org/10.1016/s0034-4257\(00\)00171-1](https://doi.org/10.1016/s0034-4257(00)00171-1).
- Stephan, E.A.; Endreny, T.A. 2016. **Weighting nitrogen and phosphorus pixel pollutant loads to represent runoff and buffering likelihoods.** Journal of the American Water Resources Association. 52(2): 336–349. <https://doi.org/10.1111/1752-1688.12390>.
- Sunset Books, eds. 1979. **Sunset new western garden book.** Menlo Park, CA: Lane. 512 p.
- Sutherland, R.C. 2000. **Methods for estimating the effective impervious area of urban watersheds.** Tech. Note 58. The Practice of Watershed Protection. Article 32: 193-195. <https://yourcleanwater.org/wp-content/uploads/2021/10/CWP-Sutherland-DCIA-Paper.pdf> (accessed Oct. 2023).
- Tropospheric Emission Monitoring Internet Service [TEMIS]. 2016. **UV index forecast and archives.** <http://www.temis.nl/uvradiation/UVindex.html> (accessed June 2016).
- U.S. Bureau of Labor Statistics. 2017. **Producer price indexes.** Washington, DC: U.S. Department of Labor, Bureau of Labor Statistics. www.bls.gov/ppi/ (accessed Dec. 2017).
- U.S. Census Bureau. 2010a. **Boundary layers depicting U.S. Census Block Groups, county subdivisions, places, counties, states, 115th Congressional District.** <https://www.census.gov>.

- [gov/geographies/mapping-files/time-series/geo/tiger-line-file.2010.html#list-tab-790442341](https://www.forestservice.gov/geographies/mapping-files/time-series/geo/tiger-line-file.2010.html#list-tab-790442341) (access Oct. 2023).
- U.S. Census Bureau. 2010b. **Census 2010: population and housing unit counts**. <https://www.census.gov/library/publications/2012/dec/cph-2.html> (accessed Oct. 2023).
- USDA Forest Service. 2004. **National forest type dataset**. Salt Lake City, UT: U.S. Department of Agriculture, Forest Service, Geospatial Technology and Applications Center. https://data.fs.usda.gov/geodata/rastergateway/forest_type/ (accessed June 2017).
- USDA Forest Service. 2014. **Wildfire hazard potential**. Version 2014. <https://firelab.org/project/wildfire-hazard-potential> (accessed June 2016).
- USDA Forest Service. 2015. **Administrative Forest and Ranger District boundaries generated by the Automated Lands Program (ALP)**. <http://data.fs.usda.gov/geodata/edw/datasets.php> (accessed June 2015).
- USDA Forest Service. 2016. **Collaborative forest landscape restoration program overview**. <https://www.fs.usda.gov/restoration/CFLRP/overview.shtml> (accessed Oct. 2023).
- USDA Forest Service. 2017. **Alien forest pest explorer**. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. <https://www.fs.usda.gov/research/nrs/products/dataandtools/interactivemaps/alien-forest-pest-explorer> (accessed Oct. 2023).
- USDA Forest Service. 2021. **Mapping and reporting**. Washington, DC: U.S. Department of Agriculture, Forest Service, Forest Health Protection. <https://www.fs.usda.gov/foresthealth/applied-sciences/mapping-reporting/index.shtml> (accessed Oct. 2023).
- U.S. Energy Information Administration. 2019a. **Average retail price of electricity to ultimate customers by end-use sector. Table 5.6.A**. Washington, DC: U.S. Department of Energy, Energy Information Administration. http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a (accessed June 2019).
- U.S. Energy Information Administration. 2019b. **Natural gas prices**. Washington, DC: Energy Information Administration, U.S. Department of Energy. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_a.htm (accessed June 2019).
- U.S. Energy Information Administration. 2019c. **Residential heating oil weekly oil and propane prices (October–March)**. Washington, DC: U.S. Department of Energy, Energy Information Administration. https://www.eia.gov/dnav/pet/PET_PRI_WFR_A_EPD2F_PRS_DPGAL_W.htm (accessed June 2019).
- U.S. Energy Information Administration. 2019d. **Residential sector energy price estimates, 2012. Table E3**. Washington, DC: U.S. Department of Energy, Energy Information Administration. http://www.eia.gov/state/seds/sep_sum/html/pdf/sum_pr_res.pdf (accessed June 2019).
- U.S. Environmental Protection Agency [U.S. EPA]. 1983. **Results of the nationwide urban runoff program: Volume I – final report**. WH-554. Washington, DC: U.S. Environmental Protection Agency, Water Planning Division. https://www3.epa.gov/npdes/pubs/sw_nurp_vol_1_finalreport.pdf (accessed March 16, 2020).

- U.S. Environmental Protection Agency [U.S. EPA]. 1999. **PCRAMMIT user's guide**. EPA-454/B-96-001. Research Triangle Park, NC: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards Emissions, Monitoring, and Analysis Division. 95 p. <https://nepis.epa.gov/Exe/ZyNET.exe/2000F6NU.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1995+Thru+1999&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C95thru99%5CTxt%5C00000017%5C2000F6NU.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL> (accessed Oct. 2023).
- U.S. Environmental Protection Agency [U.S. EPA]. 2002. **Urban stormwater BMP performance monitoring, a guidance manual for meeting the national stormwater BMP database requirements**. EPA-821-B-02-001. Washington, DC: U.S. Environmental Protection Agency, Office of Water. <https://www3.epa.gov/npdes/pubs/montcomplete.pdf> (accessed March 17, 2020).
- U.S. Environmental Protection Agency [U.S. EPA]. 2008. **Downscaler model for predicting daily air pollution**. Washington, DC: U.S. Environmental Protection Agency. <https://www.epa.gov/air-research/downscaler-model-predicting-daily-air-pollution> (accessed June 2016).
- U.S. Environmental Protection Agency [U.S. EPA]. 2012. **Environmental benefits mapping and analysis program (BenMAP)**. Washington, DC: U.S. Environmental Protection Agency. <http://www.epa.gov/benmap> (accessed Oct. 2023).
- U.S. Environmental Protection Agency [U.S. EPA]. 2013. **eGRID**. Washington, DC: U.S. Environmental Protection Agency. <http://www.epa.gov/cleanenergy/energy-resources/egrid/> (accessed Nov. 2013).
- U.S. Environmental Protection Agency [U.S. EPA]. 2015. **Smart location mapping, national walkability index**. Washington, DC: U.S. Environmental Protection Agency. <https://www.epa.gov/smartgrowth/smart-location-mapping#walkability> (accessed Oct. 2023).
- U.S. Environmental Protection Agency [U.S. EPA]. 2017a. **Air emission modeling: biogenic emissions inventory system (BEIS)**. Washington, DC: U.S. Environmental Protection Agency. <https://www.epa.gov/air-emissions-modeling/biogenic-emission-inventory-system-beis> (accessed Dec. 2017).
- U.S. Environmental Protection Agency [U.S. EPA]. 2017b. **Nonattainment areas for criteria pollutants (Green Book)**. Washington, DC: U.S. Environmental Protection Agency. <https://www.epa.gov/green-book> (accessed June 2017).
- U.S. Environmental Protection Agency [U.S. EPA]. 2018a. **Environmental monitoring community of practice; 303(d) listed impaired waters**. <https://www.epa.gov/ceam/303d-listed-impaired-waters> (accessed July 2019).

- U.S. Environmental Protection Agency [U.S. EPA]. 2018b. **Floodplain – 2018, Riparian Zones – 2016**. EnviroAtlas. Washington, DC: U.S. Environmental Protection Agency. <https://www.epa.gov/enviroatlas> (accessed June 2018).
- U.S. Environmental Protection Agency [U.S. EPA]. 2018c. **Geospatial data download service**. Washington, DC: U.S. Environmental Protection Agency. <https://www.epa.gov/frs/geospatial-data-download-service> (accessed June 2018).
- U.S. Environmental Protection Agency [U.S. EPA]. 2018d. **Version 2.1. Projected urban development based on the Integrated Climate and Land-Use Scenarios of the Fourth National Climate Assessment**. Washington, DC: U.S. Environmental Protection Agency. <https://www.epa.gov/gcx/iclus-fourth-national-climate-assessment> (accessed June 2018).
- U.S. Environmental Protection Agency [U.S. EPA] and U.S. Geological Survey (USGS). 2012. **National hydrography dataset plus (NHDPlus), version 2, 2012**. 12-digit Hydrologic Units (HUC 12). <http://www.epa.gov/waters> (accessed June 2018).
- U.S. Fish and Wildlife Service [USFWS]. 2018. **USFWS threatened & endangered species active critical habitat report**. Washington, DC: U.S. Department of Interior, U.S. Fish and Wildlife Service, Environmental Conservation Online System [ECOS]. <https://ecos.fws.gov/ecp/report/table/critical-habitat.html> (accessed June 2019).
- U.S. Geological Survey. 2013. **Land surface temperature data derived using Landsat 8 Thermal Infrared Sensor (TIR) data**. <https://www.usgs.gov/land-resources/nli/landsat/> (accessed June 2017).
- U.S. Geological Survey. 2014. **NLCD 2001 and 2011 edition percent developed imperviousness, percent canopy cover and national geospatial data asset (NGDA) land use land cover**. <https://catalog.data.gov/dataset/nlcd-2011-percent-developed-imperviousness-2011-edition-amended-2014-national-geospatial-data-> (accessed June 2015). [Data for NLCD 2001 and 2011 currently available at www.data.gov].
- U.S. Geological Survey [USGS]. 2017. **Using the USGS Landsat 8 product**. Washington, DC: U.S. Department of Interior, Geological Survey. <https://www.usgs.gov/land-resources/nli/landsat/using-usgs-landsat-level-1-data-product> (accessed June 2017).
- Valente, F.; David, J.S.; Gash, J.H.C. 1997. **Modeling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models**. Journal of Hydrology. 190(1–2): 141-162. [https://doi.org/10.1016/S0022-1694\(96\)03066-1](https://doi.org/10.1016/S0022-1694(96)03066-1).
- van Essen, H.; Schrotten, A.; Otten, M.; Sutter, D.; Schreyer, C. [et al.]. 2011. **External costs of transport in Europe, update study for 2008**. Publication code: 11.4215.50. Delft, Netherlands: CE Delft. 161 p. http://ecocalc-test.ecotransit.org/CE_Delft_4215_External_Costs_of_Transport_in_Europe_def.pdf (accessed May 7, 2019).
- Vargas, K.E.; McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Gardner, S.L.; Xiao, Q. 2007a. **Interior West community tree guide: benefits, costs, and strategic planting**. Gen. Tech. Rep. PSW-GTR-205. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 105 p. <https://doi.org/10.2737/PSW-GTR-205>.

- Vargas, K.E.; McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Gardner, S.L.; Xiao, Q. 2007b. **Temperate Interior West community tree guide: benefits, costs, and strategic planting.** Gen. Tech. Rep. PSW-GTR-206. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 108 p. <https://doi.org/10.2737/PSW-GTR-206>.
- Vargas, K.E.; McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Gardner, S.L.; Xiao, Q. 2008. **Tropical community tree guide: benefits, costs, and strategic planting.** Gen. Tech. Rep. PSW-GTR-216. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 109 p. <https://doi.org/10.2737/PSW-GTR-216>.
- Vieira, S.A.; Alves, L.F.; Aidar, M.; Araújo, L.S.; Baker, T. [et al.] 2008. **Estimation of biomass and carbon stocks: the case of the Atlantic Forest.** *Biota Neotrop.* 8(2): 21–29. <https://doi.org/10.1590/S1676-06032008000200001>.
- Viereck, L.A.; Little, E.L., Jr. 1975. **Atlas of United States trees. Vol. 2. Alaska trees and common shrubs.** Misc. Publ. 1293. Washington, DC: U.S. Department of Agriculture, Forest Service. 109 p.
- Wang, J.; Endreny, T.A.; Nowak, D.J. 2008. **Mechanistic simulation of urban tree effects in an urban water balance model.** *Journal of American Water Resource Association.* 44(1): 75–85. <https://onlinelibrary.wiley.com/doi/full/10.1111/j.1752-1688.2007.00139.x>.
- Weather Online. 2016. **Frost days.** <https://www.weatheronline.co.uk/weather/maps/city?LANG=en&PLZ= &PLZN= &WMO=11356&CONT=euro&R=160&LEVEL=162®ION=0001&LAND=OS&MOD=tab&ART=FRT&NOREGION=1> (accessed April 2016).
- Weaver, C.P.; Liang, X.Z.; Zhu, J.; Adams, P.J.; Amar P. [et al.]. 2009. **A preliminary synthesis of modeled climate change impacts on U.S. regional ozone concentrations.** *Bulletin of the American Meteorological Society (BAMA).* December (2009): 1843–1863. <https://doi.org/10.1175/2009BAMS2568.1>.
- Weng, Q.; Lu, D.; Schubring, J. 2004. **Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies.** *Remote Sensing of Environment.* 89(4): 467–483. <https://doi.org/10.1016/j.rse.2003.11.005>.
- Wesely, M.L. 1989. **Parameterization for surface resistance to gaseous dry deposition in regional-scale numerical models.** *Atmospheric Environment.* 23(6):1293–1304. <https://doi.org/10.1016/j.atmosenv.2007.10.058>.
- Westfall, J.A.; Nowak, D.J.; Henning, J.G.; Lister, T.W.; Edgar, C.B. [et al.]. 2020. **Crown width models for woody plant species growing in urban areas of the U.S.** *Urban Ecosystems.* 23(4): 905–917. <https://doi.org/10.1007/s11252-020-00988-2>.
- White, M.; Harmel, D.; Yen, H.; Arnold, J.; Gambone, M.; Haney, R. 2015. **Development of sediment and nutrient export coefficients for U.S. ecoregions.** *Journal of the American Water Resources Association.* 51(3): 758–775. <https://doi.org/10.1111/jawr.12270>.
- Wickham, J.D.; Stehman, S.V.; Gass, L.; Dewitz, J.; Fry, J.A.; Wade, T.G. 2013. **Accuracy assessment of NLCD 2006 land cover and impervious surface.** *Remote Sensing of Environment.* 130: 294–304. <https://doi.org/10.1016/j.rse.2012.12.001>.

- Wickham, J.D.; Stehman, S.V.; Gass, L.; Dewitz, J.; Sorenson, D.G. [et al.]. 2017. **Thematic accuracy assessment of the 2011 National Land Cover Database (NLCD)**. Remote Sensing of Environment. 191: 328–341. <https://doi.org/10.1016/j.rse.2016.12.026>.
- Winer, A.M.; Fitz, D.R.; Miller, P.R.; Atkinson, R.; Brown, D.E. [et al.] 1983. **Investigation of the role of natural hydrocarbons in photochemical smog formation in California: Final report**. Riverside, CA: Statewide Air Pollution Research Center. https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/41028.
- Wood, K. 2010. **Growth rates of common tree species in Westminster, Colorado**. [Place of publication unknown]: Colorado State Forest Service. 6 p. https://dspace.library.colostate.edu/bitstream/handle/10217/45095/Growth_Rates_of_Common_Tree_Species_in_Westminster.pdf?sequence=1&isAllowed=y (accessed May 7, 2019).
- Yang, Y.; Endreny, T.A. 2013. **Watershed hydrograph model based on surface flow diffusion**. Water Resources Research. 49(1): 507–516. <https://doi.org/10.1029/2012WR012186>.
- Yang, Y.; Endreny, T.A.; Nowak, D.J. 2011. **iTree Hydro: Snow hydrology update for the urban forest hydrology model**. Journal of the American Water Resources Association. 47(6): 1211–1218. <https://doi.org/10.1111/j.1752-1688.2011.00564.x>.
- Yang, Y.; Endreny, T.A.; Nowak, D.J. 2013. **A physically based analytical spatial air temperature and humidity model**. Journal of Geophysical Research Atmospheres. 118(18): 10,449–10,463. <https://doi.org/10.1002/jgrd.50803>.
- Zachry, B.C.; Booth, W.J.; Rhome, J.R.; Sharon, T.M. 2015. **A national view of storm surge risk and inundation**. Weather, Climate, and Society. 7(2): 109–117. <http://dx.doi.org/10.1175/WCAS-D-14-00049.1>.
- Zanne, A.E.; Lopez-Gonzalez, G.Z.; Coomes, D.A.; Ilic, J.; Jansen, S. [et al.]. 2009. **Data from: Towards a worldwide wood economics spectrum**. Durham, NC: Dryad Digital Repository. <https://doi.org/10.5061/dryad.234>.
- Zinke, P.J. 1967. **Forest interception studies in the United States**. In: Sopper, W.E.; Lull, H.W., eds. Forest hydrology. Oxford, UK: Pergamon Press: 137–161.

REFERENCES LISTED IN APPENDIX 6

State-specific sources for invasive trees and shrubs; see appendix 6 for details. Some of the listed web addresses are no longer functional but were active at the time of the development of the invasive tree and shrub database.

Alabama Invasive Plant Council. 2007. **2007 plant list**. Athens, GA: Center for Invasive Species and Ecosystem Health, Southeast Exotic Pest Plant Council. <https://accs.uaa.alaska.edu/invasive-species/non-native-plant-species-list/>.

Alaska National Heritage Program. 2014. **Non-Native plant data**. Anchorage, AK: University of Alaska Anchorage. <https://accs.uaa.alaska.edu/invasive-species/non-native-plant-species-list/>.

Arizona Wildland Invasive Plant Working Group. 2005. **Invasive non-native plants that threaten wildlands in Arizona**. Phoenix, AZ: Southwest Vegetation Management Association <https://www.swvma.org/wp-content/uploads/Invasive-Non-Native-Plants-that-Threaten-Wildlands-in-Arizona.pdf>.

Ashigh, J. Wanstall, J., Sholedice, F. 2010. **Troublesome weeds of New Mexico**. La Cruces, NM: New Mexico State University, College of Agricultural, Consumer and Environmental Sciences, Cooperative Extension Service. 104 p. https://www.nmda.nmsu.edu/wp-content/uploads/2012/04/troublesome_weeds_nm.pdf.

California Invasive Species Advisory Committee. 2010. **The California invasive species list**. Sacramento, CA: Invasive Species Council of California. <http://www.iscc.ca.gov/docs/CaliforniaInvasiveSpeciesList.pdf>.

Center for Invasive Species and Ecosystem Health. 2009. **Illinois invasive plant list**. Athens, GA: Center for Invasive Species and Ecosystem Health, [Invasive.org](http://invasive.org). https://extension.illinois.edu/sites/default/files/invasive_plant_species_regulated_by_the_illinois_exotic_weed_act.pdf.

City of Austin, TX. **Central Texas invasive plants**. https://www.austintexas.gov/sites/default/files/files/Watershed/invasive/2013_Invasives_guide_small.pdf.

Colorado Weed Management Association. 2012. **Colorado's noxious weed list**. Arvada, CO: Colorado Weed Management Association. <https://cwma.org/weed-information/weed-list/>.

Connecticut Invasive Plant Working Group. 2013. **Invasive plant list**. Storrs, CT: University of Connecticut. http://cipwg.uconn.edu/invasive_plant_list/.

Cusack, C.; Plumb, S.; Prince, D. 2011. **Developing invasive plant outreach and management projects**. Montpelier, VT: The Nature Conservancy (see Table 1.2).

Cygan, D. 2011. **New Hampshire guide to invasive upland plant species, 3rd edition**. Concord, NH: Department of Agriculture, Division of Plant Industry. <http://www.agriculture.nh.gov/publications-forms/documents/upland-invasive-species.pdf>.

Delach, A. n.d. **Invasive species in Utah**. <https://defenders.org/sites/default/files/publications/utah.pdf>.

- Florida Exotic Pest Plant Council. 2007. **Florida EPPC's 2007 invasive plant species list.** Athens, GA: Center for Invasive Species and Ecosystem Health, Southeast Exotic Pest Plant Council. <https://floridainvasivespecies.org/plantlist.cfm>.
- Forest Invasive Plants Resource Center. 2006. **Iowa.** U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry. https://www.fs.usda.gov/foresthealth/docs/fhh/IA_FHH_2006.pdf.
- Georgia Exotic Pest Plant Council. 2006. **List of non-native invasive plants in Georgia.** Athens, GA: Center for Invasive Species and Ecosystem Health, Southeast Exotic Pest Plant Council. <https://www.gaepcc.org/list/>.
- Grafton, E. 2003. **Dirty dozen.** Charleston, WV: West Virginia Division of Natural Resources, Wildlife Resources. <http://www.wvdnr.gov/Wildlife/DirtyDozen.shtm>.
- Hawaii State Alien Species Coordinator. 2012. **Hawaii's most invasive horticultural plants.** Honolulu, HI: Department of Land and Natural Resources, Division of Forestry and Wildlife. <https://www.biisc.org/wp-content/uploads/hawaiis-most-invasive-horticulture-plants-compressed.pdf>.
- Idaho Association of Weed Superintendents and University of Idaho Extension Office. 2020. **Invasive species of Idaho.** <http://invasivespecies.idaho.gov/terrestrial-plants>.
- Illinois Department of Natural Resources. 2020. **Invasive species.** <https://www2.illinois.gov/dnr/conservation/IWAP/Pages/InvasiveSpecies.aspx>.
- Illinois Department of Natural Resources. 2020. **Invasive species campaign.** <https://www2.illinois.gov/dnr/conservation/IWAP/Documents/InvasiveSpecies.pdf>.
- Indiana Cooperative Agricultural Pest Survey. 2007. **Indiana's "Most Unwanted" invasive plant pest list - FY 2007.** West Lafayette, IN: Purdue University, Purdue Extension Entomology. https://www.entm.purdue.edu/iisc/pdf/IN_Regulated_Terrestrial_Invasive_Plant_Species_Guide_small.pdf.
- Indiana Department of Natural Resources. 2020. **Invasive plant species.** <https://www.in.gov/dnr/naturepreserve/4736.htm>.
- Indiana Invasive Species Council. 2020. **Official IISC invasive plant list.** <https://www.entm.purdue.edu/iisc/invasiveplants.html>.
- Invasive Native Plant Society of New Jersey. 2004. **Appendix to policy directive 2004-02 invasive nonindigenous plant species.** <https://www.nj.gov/dep/commissioner/policy/pdir2004-02.htm>.
- Iowa Department of Natural Resources. **Invasive plants.** Des Moines, IA: Department of Natural Resources, Forestry Bureau. <http://www.iowadnr.gov/Environment/Forestry/ForestHealth/InvasivePlants.aspx>.
- Jardine, J.; Witsell, T. n.d. **Working list of non-native invasive plant species of concern to natural areas in Arkansas.** Arkansas Native Plant Society. <https://www.baxtercountymg.com/invasive-non-natives.html>.
- Kansas Forest Service. 2020. **Invasive species.** https://www.kansasforests.org/forest_health/invasivespecies.html.

- Kansas Native Plant Society. 2006. **Invasive plants of Kansas**. Lawrence, KS: University of Kansas, R.L. McGregor Herbarium. <https://www.kansasnativeplantsociety.org/wp-content/uploads/2021/03/InvasivePlantFactSheet.pdf>.
- Kentucky Exotic Pest Plant Council. 2013. **Kentucky exotic pest plant council**. Athens, GA: Center for Invasive Species and Ecosystem Health, Southeast Exotic Pest Plant. <http://www.se-eppc.org/ky/list.htm>.
- Ling, H. 2003. **Invasive plant species**. Native Plant Society of New Jersey. http://www.npsnj.org/articles/invasive_plant_species.html.
- Maine Legislature. 2000. **An act to prevent the spread of invasive aquatic plants**. Augusta, ME: Maine State Legislature, Office of the Revisor of Statutes. <http://www.mainelegislature.org/ros/LOM/LOM119th/5Pub701-750/5Pub701-750-21.htm>.
- Maine Department of Agriculture, Conservation, and Forestry. Various dates. **Maine invasive plant fact sheets**. Augusta, ME: Department of Agriculture, Conservation, and Forestry, Maine Natural Areas Program. http://www.maine.gov/dacf/mnap/features/invasive_plants/invsheets.htm.
- Maryland Invasive Species Council. 2014a. **Invasive species of concern in Maryland: terrestrial plants**. <https://mdinvasives.org/species-of-concern/>.
- Maryland Invasive Species Council. 2014b. **Invasive species of concern in Maryland: aquatic plants**. <https://mdinvasives.org/species-of-concern/aquatic-plants>.
- Massachusetts Invasive Plant Advisory Group. 2005. **The evaluation of non-native plant species for invasiveness in Massachusetts**. http://www.massnrc.org/mipag/docs/MIPAG_FINDINGS_FINAL_042005.pdf.
- McAvoy, W.A. 2001. **Invasive plant species in Delaware**. Dover, DE: Department of Natural Resources and Environmental Control. <http://delawareinvasives.net>.
- Michigan Natural Features Inventory. 2014. **Michigan invasive plant species accounts**. Lansing, MI: Michigan State University Extension, Michigan Natural Features Inventory. <https://mnfi.anr.msu.edu/invasive-species/InvasivePlantsFieldGuide.pdf>.
- Minnesota Department of Natural Resources. 2014a. **Invasive terrestrial plants**. <http://www.dnr.state.mn.us/invasives/terrestrialplants/index.html>.
- Minnesota Department of Natural Resources. 2014b. **Invasive aquatic plants**. <http://www.dnr.state.mn.us/invasives/aquaticplants/index.html>.
- Mississippi Exotic Pest Plant Council. 2014. **Noteworthy exotic plant species of Mississippi**. Athens, GA: Center for Invasive Species and Ecosystem Health, Southeast Exotic Pest Plant. http://www.se-eppc.org/mississippi/MS_EPPCList_Ranking_Guidelines.pdf.
- Missouri Botanical Garden. 2002. **Missouri exotic pest plants**. St. Louis, MO: Missouri Botanical Garden. <http://www.mobot.org/mobot/research/mepp/alphalist.shtml>.
- Missouri Department of Conservation. 2020. **Invasives**. <https://mdc.mo.gov/trees-plants/invasive-plants>.

- Native Plant Society of New Jersey. 2004. **Appendix to policy directive 2004-02 invasive nonindigenous plant species.** https://npsnj.org/wp-content/uploads/2023/01/invasive_plant_list.pdf.
- Nebraska Invasive Species Advisory Council. N.d. **Invasive plants of Nebraska.** <https://neinvasives.com/ecoregions/all>.
- New Hampshire Department of Agriculture. 2012. **Prohibited invasive plant species rule.** Concord, NH: Department of Agriculture, Division of Plant Industry. <http://www.agriculture.nh.gov/publications-forms/documents/prohibited-invasive-species.pdf>.
- New Hampshire Department of Agriculture. 2014. **List of restricted species.** Concord, NH: Department of Agriculture, Division of Plant Industry. <http://www.agriculture.nh.gov/publications-forms/documents/restricted-invasive-species.pdf>.
- New Mexico Department of Agriculture. 2020. **Noxious weed information.** <https://www.nmda.nmsu.edu/nmda-homepage/divisions/apr/noxious-weed-information/>.
- New York State Department of Environmental Conservation. 2020. **Invasive species regulations.** <https://www.dec.ny.gov/animals/99141.html>.
- New York State Department of Environmental Conservation. **Interim invasive species plant list.** <http://www.dec.ny.gov/animals/65408.html>.
- North Carolina Native Plant Society. 2010. **Invasive exotic species list.** Greensboro, NC: North Carolina Native Plant Society. <http://www.ncwildflower.org/invasives/list.htm>.
- North Dakota Department of Agriculture. 2020. **Noxious weeds.** <https://www.nd.gov/ndda/plant-industries/noxious-weeds>.
- North Dakota Department of Agriculture. **Catalogue of species.** [URL no longer available.].
- Northwest Illinois Forestry Association. 2020. **Exotic invasive plants.** <http://www.nifatrees.org/Invasive-Species>.
- Ohio Department of Agriculture. 2018. **Invasive plants.** <https://agri.ohio.gov/wps/portal/gov/oda/divisions/plant-health/invasive-pests/invasive-plants>.
- Ohio Division of Natural Areas and Preserves. 2000. **Ohio's invasive plant species.** Columbus, OH: Department of Natural Resources, Division of Natural Areas and Preserves.
- OK Invasives. 2020. **Invasive species to keep an eye on!** <https://www.okinvasives.org/watch-list-1>.
- Oklahoma Native Plant Society; Oklahoma Biological Survey; OSU Natural Resource Ecology and Management. **Oklahoma non-native invasive plant species.** Norman, OK: Oklahoma Invasive Plant Council. [URL no longer available.]
- Pennsylvania Department of Conservation and Natural Resources. **Invasive Plants in Pennsylvania.** Harrisburg, PA: Department of Conservation and Natural Resources. <https://www.dcnr.pa.gov/Conservation/WildPlants/InvasivePlants>.

- Pernas, T.; Giardina, D.; Duquesnel, J.; Franck, A.; Hammer, R.L. [et al.]. 2019. **Florida Exotic Pest Plant Council's 2019 list of invasive plant species**. http://bugwoodcloud.org/CDN/fleppc/plantlists/2019/2019_Plant_List_ABSOLUTE_FINAL.pdf.
- Rhode Island Invasive Species Council; Rhode Island Natural History Survey. 2001. **Invasives: list**. https://rinhs.org/wp-content/uploads/2021/10/Invasive-and-Weedy-Plants-in-RI-2020_-FINAL.pdf.
- Smith, C. 2008. **Invasive exotic plants of North Carolina**. Charlotte, NC: North Carolina Department of Transportation. http://www.se-eppc.org/northcarolina/NCDOT_Invasive_Exotic_Plants.pdf.
- South Carolina Exotic Pest Plant Council. 2008. **Invasive species list 2008**. Athens, GA: Center for Invasive Species and Ecosystem Health. <http://www.invasive.org/species/list.cfm?id=27>.
- South Dakota Department of Agriculture. 2020. **State noxious weed & pest list**. <https://sdda.sd.gov/ag-services/weed-and-pest-control/weed-pest-control/sd-state-noxious-weed-declared-pest-list-and-distribution-maps/>.
- State of Michigan. 2020. **Michigan invasive species**. https://www.michigan.gov/invasives/0,5664,7-324-68002_71240_73850---,00.html.
- Stoddard, S.W.; Johnson, W.S.; Wilson, R.E. **Invasive plants in Nevada: An identification handbook**. SP 96-01. Reno, NV: University of Nevada, Cooperative Extension. <https://arrowcreek411.files.wordpress.com/2018/08/nv-invasive-plants.pdf>.
- Tennessee Exotic Pest Plant Council. 2009. **TN-EPPC invasive exotic pest plants in Tennessee**. Fairview, TN: Tennessee Exotic Pest Plant Council. <https://sites.google.com/site/tnarboretum/Home/tn-eppc-invasive-exotic-pest-plants-in-tennessee>.
- Tennessee Invasive Plant Council. 2020. **TN-IPC 2017 list revision**. <https://www.tnipc.org/revised-list-of-invasive-plants>.
- TexasInvasives.org. 2020. **Invasives database**. https://texasinvasives.org/plant_database/coal_results.php?offset=12.
- USDA Natural Resources Conservation Service, Plants Database. 2017. **Introduced, invasive, and noxious plants [for Oregon]**. <https://plants.usda.gov/home/noxiousInvasiveSearch>.
- USDA Natural Resources Conservation Service. 2017. **Introduced, invasive, and noxious plants [for Washington]**. <https://plants.usda.gov/java/noxious?rptType=State&statefips=53>.
- USDA Natural Resources Conservation Service. 2017. **Introduced, invasive, and noxious Plants [for West Virginia]**. <https://plants.usda.gov/java/noxious?rptType=State&statefips=54>.
- Vermont Invasive Exotic Plant Committee. 2005. **Invasive species watch list for Vermont**. https://fpr.vermont.gov/sites/fpr/files/Quarantine_WatchListUpdate-2017_November.pdf.
- Virginia Department of Conservation and Recreation. 2009. **Invasive alien plant species of Virginia**. Richmond, VA: Department of Conservation and Recreation, Division of Natural Heritage. Original URL unavailable. Updated list: <https://www.dcr.virginia.gov/natural-heritage/document/nh-invasive-plant-list-2014.pdf>.

- Watershed Protection Development Review. N.d. **Central Texas invasive plants**. Austin, TX: City of Austin, Watershed Protection Development Review. https://www.austintexas.gov/sites/default/files/files/Watershed/invasive/2013_Invasives_guide_small.pdf.
- Winters, F.; Byrd, J.D.; Bryson, C.T. N.d. **Mississippi's 10 worst invasive weeds**. Mississippi State, MS: Mississippi State University, Extension Services. <http://www.se-eppc.org/pubs/m1194.pdf>.
- Wisconsin Department of Natural Resources. 2018. **Terrestrial invasive species**. <https://dnr.wisconsin.gov/sites/default/files/topic/Invasives/ISLegReport2018.pdf>.
- WVDNR Natural Heritage Program. 2009. **Invasive plant species of West Virginia**. <http://www.wvdnr.gov/wildlife/Handout%20Invasive%20Plants%20of%20WV%202009.pdf>.
- Wyoming Weed and Pest Council. 2019. **State designated noxious weeds**. <https://wyoweed.org/noxious-species/listed-species/state-designated-noxious-weeds/>.

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720-2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877-8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at http://www.ascr.usda.gov/complaint_filing_cust.html and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632-9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250-9410; (2) fax: (202) 690-7442; or (3) email: program.intake@usda.gov.
