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Abstract

Currently, stakeholders lack a comprehensive understanding of carbon storage in urban ecosystems, resilience of urban forests to projected climatic fluctuations, and variation in both across an urban continuum. We aimed to fill these important knowledge gaps by building upon existing regional-scale urban forest datasets with rigorous analysis of carbon storage in urban soils, trends in urban tree growth, and the development and validation of an urban tree site index. The outcomes of this work provide a more complete understanding of urban ecosystem carbon sequestration and storage potential and the response of urban trees to projected climate change across a metropolitan region.

Progress Achieved in Accomplishing Project Objectives

This project was comprised of three major objectives, listed individually below. We amassed a great deal of data and information during the course of the grant period. This report provides a brief summary of the project components and results. Details can be found on the Chicago Urban Forest Study website (www.chicagourbanforeststudy.com) and in the upcoming publications listed in this report.

Major Findings

1. Annual tree growth the urban forest continuum is driven primarily by climatic components, and is most strongly associated with growing season (May-Oct) Palmer Drought Severity Index (a measure of drought severity based on temperature, precipitation, and moisture availability).
2. Trees growing in park and residential land-use classes exhibit significantly higher rates of productivity than trees growing in other land-uses.
3. Resistance to drought was significantly lower during the recent 2012 drought, as compared to the 2005 and 1988 droughts.
4. The majority of soil organic carbon (SOC) in the Chicago region urban ecosystem is contained in deeper soil layers.
5. It appears that SOC in the Chicago region urban ecosystem exceeds SOC contents in other non-urban terrestrial systems, and is similar to SOC storage of other urban ecosystems.
6. Spatial patterns in SOC were most related to surface soil properties and anthropogenic factors and these factors might be used for predictive mapping of urban ecosystem SOC.
7. The Revised Urban Site Index (RUSI) did well to accurately quantify the quality of urban sites for tree growth.

Objective I: Urban Forest Resilience

The goals of this research were to assess how tree growth and sensitivity to site and climate conditions vary across land-uses and species within the urban forest continuum. This research was conducted to generate knowledge on the expected response of urban and community forests to extreme climate events, particularly drought, and the drivers behind this response. This knowledge will hopefully serve as an important guide for communities as they adapt and manage their forests to projected climate change. Results presented here have three parts: (1) a comprehensive tree-ring chronology for growth and climate signal evaluation, (2) variability in productivity and resistance and resilience to drought across urban land-use classes, and (3) site conditions and constraints as potential drivers of productivity and drought sensitivity in the urban forest.

Increment cores from a total of 609 trees across 90 sites and five land-use classes were extracted and used for growth, productivity, and climate response analysis, providing substantial insight into the variability in growth rates and climate sensitivity in the urban landscape. A comprehensive dendrochronological assessment was performed to identify the climate-growth relationships in the urban landscape to determine the suitability of urban trees in climate signal identification. We developed composite aggregate and land-use, multi-species three-decade tree-ring chronologies for the Chicago urban forest continuum. Although the average interseries correlation was low (0.23), it was not unexpected, and a positive coefficient indicates that a perceptible signal exists. When tested against climate variables – precipitation and Palmer Drought Severity Index (PDSI) – we found that a fairly strong climate signal exists in the tree-ring record. Radial growth, both across the landscape within land-use classes, was positively correlated with both precipitation and PDSI. Growing season (May-October) PDSI accounts for approximately half of the total variance within the land-use class growth chronologies ($r = 0.53$ – 0.75), suggesting that moisture availability is a limiting agent in tree growth across the entire landscape ($r = 0.78$) and also on the individual land-use scale. These strong relationships indicate that trees within the urban forest continuum do provide an adequate climate signal, land-use can be used as an appropriate indicator of urban forest climate response, and that, for future needs, components of PDSI will be relevant for tree growth across the urban land-use gradient.

Further results confirm significant differences in productivity across land-use classes, with trees growing in sites with higher light availability and lower competition (e.g., park, residential) exhibiting higher rates of productivity over the last three decades, and agricultural sites, defined primarily as riparian buffer zones and remnant interstitial stands, and forest sites routinely demonstrating lower rates of productivity. Drought resistance, defined as the ability of a tree to maintain growth under drought conditions, was not significantly different among land-use classes for the three drought years evaluated (2015, 2005, 1988). However, resistance was considerably lower in 2012 across all land-uses, suggesting that drought severity, timing, and/or duration may be important contributors to growth response. Drought resilience, or the ability of a tree to return growth to pre-drought level in the period following drought, also did not vary among land-use classes and growth generally returned to pre-drought levels in the years following drought. However, both drought response indices did vary among some of the common genera in the urban forest (*Acer*, *Fraxinus*, *Prunus*, *Quercus*, *Ulmus*), with significant interaction between land-use classes and genera. This leads us to think that although species-specific physiology may be a more important driver in drought response, even in the urban landscape, growing conditions are not an insignificant contributor.

The third component of this research evaluated the effect of site conditions and edaphic constraints on productivity and drought resistance and resilience. Initial models testing a suite of site parameters (e.g. soil characteristics, ground cover, various metrics of urbanization, canopy height and diversity) suggest that site factors are not the primary driver of either productivity or drought response, and thus the differences between sites may not be as great as expected. These results are not dissimilar from the previously discussed land-use evaluation of drought resistance and resilience, as we did not detect significant differences in drought response across land-use classes but rather species.

Preliminary results were presented at the Ecological Society of America annual meeting in August 2014 in the urban ecosystems session and at The Morton Arboretum Urban Tree Conference in November 2014 (see: Symposium). A manuscript on the comprehensive evaluation of urban forest productivity and drought resilience is in preparation and will be submitted to Ecosphere in 2015. This paper will also be presented at the April 2015 Association of American Geographers Annual Meeting in Chicago. A manuscript on the suitability of climate-driven dendrochronological analysis in the urban landscape will be submitted to the Journal of Biogeography in 2015.

Additionally, this research will contribute to an integrated mapping framework of regional-scale data sets (see: Website). This framework was presented by co-PI Fahey in October 2014 at the National Workshop on Large Landscape Conservation in Washington, D.C.

Objective II. Carbon Sequestration of Urban Trees and Soils

This research was conducted to address the knowledge gap in urban soil C storage. The results from this research are threefold: 1) a more comprehensive understanding of soil organic C (SOC) storage and C sequestration of urban trees and soils to supplement C sequestration models for urban and community forests, 2) improve our source and sink projections of urban SOC and provide a better understanding of the SOC dynamics of these soils as they are disturbed or subjected to climate change, and 3) improve our understanding of urban soils as we utilize them for various other ecosystem services, such as growing plants, storing and cleaning water.

A total of 190 plots were stratified and sampled across five land-use classes in the Chicago seven county region. Two intact deep soil cores to a 1-m depth were collected on each of these plots as well as a ten-core composite from the surface (0-20 cm). Soil horizons were identified and sampled to determine organic C concentration, bulk density and other morphological properties (e.g, texture, structure). Surface soils were analyzed for physical, chemical and biological properties, which were used in our modeling to predict SOC storage. In total, 1,293 samples were characterized to determine SOC by depth distributions across the Chicago urban ecosystem. We tested three hypotheses with this data:

1. The majority of urban SOC will be contained in deeper soil layers.
2. SOC in this urban ecosystem (Chicago region) will meet or exceed SOC contents in other terrestrial systems.
3. Spatial patterns in urban SOC will be most related to vegetation patterns and anthropogenic factors and not related to other soil forming factors of relief, parent material and climate.

Our first hypothesis was confirmed and we found approximately 75% of SOC at depths greater than 25 cm. As expected, the concentration of SOC (%) is greatest at the surface and decreases with depth. However, due to increases in soil density with depth the stock of SOC (kg m-2) increases with depth, peaking in the 50-80 cm depth. This finding is very important given that the vast majority of research attempting to detail urban SOC storage has often focused on surface soil sampling, which would substantially underestimate the actual SOC stock in urban soils. We are using our data to develop models by urban land-use to predict SOC storage to 1-m with surface soil SOC content and concentration.

The second hypothesis that urban SOC stock is large when compared to other non-urban systems is supported. The mean SOC stock to a 1-m depth across the Chicagoland ecosystem was 36 kg m^{-2}, with a range of 4-132 kg m^{-2}. These soils contain much greater amounts of SOC compared to forest and prairie soils (7-15 kg m^{-2}). Urban SOC storage was not found to be as large as organic soils in wetlands, which often contain approximately 200 kg m^{-2}. The SOC stock of the Chicagoland region is similar to soils measured Hong Kong (42 kg m-2), less than the stocks measured in Moscow (157 kg m^{-2}) and New York (157 kg m^{-2}); and, greater than stocks in Washington DC (15 kg m^{-2}) and Baltimore (9 kg m^{-2}). The data collected in this research on SOC storage is one of the most intensive efforts towards detailing SOC stocks across a major metropolitan area and provides a significant contribution to our understanding of SOC storage in urban soils. Our data provide evidence towards to disproving the common misconception that urban soils are deficient in organic matter. This finding is very important considering the intensive management with synthetic fertilization that occurs (often without any soil assessment) in urban landscapes. This management practice is predicated on the belief of low organic matter in urban soils. Reduction in synthetic fertilization in urban landscapes will reduce potential contamination of surface and groundwater, reduce volatilization of nitrogen to the atmosphere and reduce management costs.

Our last hypothesis was partly supported, in that our models were able to predict urban SOC storage with a variety of anthropogenic factors (e.g, land-use, impervious surface area). However, inclusion of vegetation factors, such as basal area and increment growth, did not improve SOC models. Furthermore, other soil forming factors related to climate, relief and parent material were not useful in predicting urban SOC. One implication of this finding is that the standard model utilizing genetic factors of climate, organisms, relief, parent material and time to predict soil properties cannot be applied to the urban landscapes. Consequently, when attempting to map soils in the urban ecosystem, more emphasis should be placed on anthropogenic factors. This is an important finding given the increasing effort by the USDA-NRCS to map urban soils. Future research will be directed towards refining of our urban SOC models and testing them with remotely sensed data. It is our hope that these models might eventually be developed into spatial data layers, which could then be tested across other urban ecosystems.

Preliminary results were presented at The Morton Arboretum Urban Tree Conference in November 2014. A manuscript is in preparation to be submitted to Soil Science Society of America Journal in 2015. This paper will also be presented at a Special Session on Urban Soil Carbon Storage at the November 2015 Soil Science Society of America Meeting in Minneapolis, MN. Bryant Scharenbroch is organizing this session, which is sponsored by the Urban and Anthropogenic Soils Division of SSSA. Other presenters in the session include leaders in the field of urban soil research, such as Drs. Rattan Lal (Ohio State U), Richard Pouyat (USDA-FS), Darrel Jenerette (UC-Riverside), Mitchell Pavao-Zuckerman (U Arizona) and Tara Trammell (U Delaware). A goal of this session is to bring this group of folks together in a discussion to facilitate collaboration and possibly develop a future agenda on the topic of urban soil carbon storage.

Objective III. Revised Urban Site Index

The goal of the research was to validate the Revised Urban Site Index (USI) rapid assessment process for its ability to accurately quantify the quality of urban sites for tree growth. The RUSI model was developed from our first model published in Scharenbroch et al. 2012, and with collaboration of more than 10 partners over a two-year period. The RUSI hopes to be an invaluable resource for managers, planners and municipalities, and landowners for matching site characteristics with vegetation tolerances to maximize urban forest health. Results indicate that the USI is a good predictor of tree health and growth. Because the RUSI tool is field-based, inexpensive, and can be easily incorporated into existing databases, it is also very practical.

To the develop and test the RUSI model site, soil and tree data were collected and analyzed from 40 plots in each of the following eight cities, for a total of 320 plots in four states: Boston, MA, Chicago, IL, Cleveland, OH, Ithaca, NY, Naperville, IL, New York, NY, Springfield, MA, and Toledo, OH. In this study, we focused on limited set of tree species including *Acer rubrum*, *Quercus rubra* and *Tilia cordata*. In brief the RUSI assessment includes 5 factors (climate, urban, soil physical, chemical and biological). Each factor has 3 field-based assessments which are scored 0-3. The RUSI tool can be scaled to the user's preference and abilities. To date, our data analyses show that the RUSI is a reliable predictor of urban tree condition. We are still analyzing the data to test if RUSI is a reliable predictor of urban tree growth. Future research on the RUSI project will be to test this model across a broader geographic range and across a wider species list.

The USI model is being incorporated into the Urban Tree Monitoring protocols being developed by the Urban Tree Growth & Longevity Working Group of the International Society of Arboriculture. The research and model developed in the RUSI project were implemented in writing the Best Management Practices: Soil Management for Urban Trees (Scharenbroch et al. 2014). A final manuscript on this research will be submitted to Urban Forestry & Urban Greening journal in 2015. Preliminary results from the RUSI research had been presented and discussed at six local, regional, and international meetings during 2013-2014 grant period:

- International Society of Arboriculture. Milwaukee, WI. 08/05/14.
- The Holden Arboretum Scientist Lecture. Kirtland, OH. 02/20/14.
- Midwestern Chapter of International Society of Arboriculture. Dubuque, IA. 01/31/14.
- Professional Landscape Management School. Evansville, IN. 01/30/14.
- Urban Tree Selection and Planting Conference. Morton Arboretum. Lisle, IL. 11/18/13.
- Ohio Annual Foresters Conference. Toledo, OH. 10/24/13.

Final results will be presented at the International Society of Arboriculture in Tampa, FL in 2015. The RUSI model will be available to the public on the project website, with helpful items including introductory information to the model, data collection protocols, species hardiness ratings, and collaboration opportunities.

Scharenbroch, B.C. & M. Catania. 2012. Soil quality attributes as indicators of urban tree performance. Arbor. & Urb. For. 38:214-228.
Scharenbroch, B.C., E.T. Smiley and W. Kocher. 2014. Best Management Practices: Soil Management for Urban Trees. International Society of Arboriculture. Champaign, IL.

Symposium
The Morton Arboretum hosted a two-day Urban Tree Conference titled "Managing Urban Forests in a Changing Climate" on November 18-19, 2014. This symposium was open to the public and presented in partnership with the USDA Forest Service and its Northern Institute of Applied Climate Science. Continuing Education Credits were offered to participants through the International Society of Arboriculture. The audience included researchers, land managers, municipalities, foresters and arborists, and other public and private landowners and decision-makers interested in research associated with climate change in the urban landscape and the associated practical concerns (e.g., mitigation, management applications, species resilience and suitability). A total of 126 participants from 15 states and two countries attended the meeting. Both scientists and practitioners spoke at the symposium on a variety of topics ranging from drought resistance and urban carbon storage, to climate change driven shifts in pests and diseases and extreme storm damage and water management, to understanding overall urban forest vulnerability and practical management approaches to climate change.

Objectives I and II were presented here by Bialecki and Scharenbroch, respectively. A lecturecast is available for the project presentations, and audio supported slides will be accessible on the project website.

Project Website
A website was created at the launch of the project in 2013 **(www.chicagourbanforeststudy.org).** The website initially provided an overview of the research goals and a platform for landowners to accept or decline the request for permission to conduct sampling on their property. The site was updated during the course of the project on the progress, symposium details, and expected timeline of completion. The site will be maintained for a total of 10 years and will store products associated with this research, as described below.

Data
All compiled tree-ring and soils data will be available for public use. Private property addresses and landowners will be removed, and we will account for other privacy issues.

Publications
Bialecki, M.B., B.C. Scharenbroch, and R.T. Fahey. (In prep). Landscape-level assessment of tree growth-climate relationships in the Chicago urban forest. For submission to Landscape Ecology.

Bialecki, M.B., Fahey, R.T., and B.C. Scharenbroch. (In prep). Variations in tree productivity and drought vulnerability across the urban landscape. For submission to Ecosphere.

Scharenbroch, B.C., Bialecki, M.B., Fahey, R.T., and M. Catania. (In prep). Distribution and factors controlling soil organic C in the Chicago region. For submission to Soil Science Society of America Journal.

Scharenbroch, B.C., Catania, M., Bialecki, M.B., Carter, D., Fahey, R.T., Siewert, A., Miller, S., Bassuk, N., Harper, R., Raciti, S., Pouyat, R., Lu, J. and N. Auyeung. (In Prep). An urban site index for assessing planting sites for trees. For submission to Urban Forestry and Urban Greening.

Presentations
Slides and audio for both presentations on urban carbon storage and urban forest resilience from the Urban Tree Conference (see: Symposium) will be available for public viewing.

Products

1. Data and mapping tools
   Tree growth and response models will be integrated with an Urban Tree Canopy Assessment that is being developed by the USFS Northern Research Station and Chicago Region Trees Initiative (a cooperative regional effort lead by The Morton Arboretum, Chicago Wilderness, and Openlands). Data from this project will be used to validate biomass models and also to predict C sequestration and growth in conjunction with other regional datasets. Data and model predictions will be incorporated into the Chicago Wilderness Green Infrastructure interactive mapping framework (www.fieldmuseum.org/science/microsites/gis-science-and-education/gis-science-and-education-interactive-maps). This collaborative effort will be linked on the Chicago Urban Forest Study project site.
2. Urban C Storage Model
   The urban SOC models will be available to public from our website. We will also share the data and findings with scientists working on the i-Tree tools with the hopes that the data might be utilized to improve assessment of ecosystem services by including the oft-overlooked but signification soil component. Our soil morphological data will be shared with the USDA-NRCS office in Aurora, IL who are currently working on mapping urban soils in the Chicagoland region.
3. RUSI
   The RUSI model will be available to the public to use as a tool to assess the quality of planting sites for urban trees. RUSI items on the project website include an introduction to RUSI, field data collection protocol, and interpretation guidelines. In addition, procedures to submit data will be included. This data will be used for future testing of the RUSI tool across broader geographic areas and a broader species pool.

User Feedback
The site will allow for viewers and users of the data and products to provide feedback on

the value of data and research, its applications and user friendliness. The site will be modified over time according to requested specifications.

Future Directions

Objective I

Evaluating drought resilience following the 2012 drought will be important, particularly as resistance to the 2012 drought was significantly lower than previous droughts. Comparing resilience of the 2012 drought to the 2005 and 1988 drought will provide more insight on the ability of the urban forest to withstand more severe, multi-season droughts coupled with high temperatures, and the influence of drought duration and timing on response, sensitivity, and mortality.

Additionally, implementing methods that quantify the role of the urban heat island on growth and drought response may be an appropriate future step. Although Objective I of this project included site characteristics and different measures of urbanization (site level and regional impervious surface cover, distance to urban center), we observed no significant variation in sites across the landscape, and no overwhelming influence of urban site characteristics on growth and resistance on the landscape level. However, microclimate at the site level, specifically temperature and associated evapotranspiration, may help identify the extent of the urban heat island effect in the urban forest continuum, and may be useful to managers and municipalities when managing the forest canopy for the long-term.

The Morton Arboretum and partners will also be linking data and results from the NUCFAC study to biomass and productivity estimates from remotely-sensed data such as the Urban Tree Canopy assessment and LiDAR (see: Website). This will be helpful in the development of the Chicago Wilderness Green Infrastructure interactive mapping framework.

Objective II

Understanding carbon storage and dynamics in urban ecosystems will become increasingly important in the future as urban areas continue to expand. Furthermore as carbon accounting efforts expand we will need to know more of the potential of these ecosystems to sequester and release carbon. Given the heterogeneity of urban ecosystems, this will be a difficult task.

This study provides a framework for other large metropolitan areas across the globe to mimic for investigate urban SOC storage. We emphasize that it is critical to consider that the majority of SOC appears to be stored in deeper soil layers. Therefore, shallow soil sampling does not appear valid unless accurate depth by SOC content models can be created and utilized. Our data might be used to develop these models, and we are exploring this as an important next step for our research. Our predictive models for SOC are still in development, but upon publication, they might be tested in other urban ecosystems to predict SOC storage.

Objective III

The Revised Urban Site Index (RUSI) model appears to be relatively accurate for predicting urban tree growth and health for the cities that we have developed and tested it in. However, all of these cities are within the temperate climate where precipitation exceeds evapotranspiration for most of the growing season and mean annual temperature range from 0-15°C. Furthermore the model has been created and tested on a relatively limited number of tree species. Future research on the RUSI project will be directed towards testing the model across a broader geographic range and across a wider species list. We will also be working towards making the model more accessible to user through a web-based platform. The web site will contain protocols for using model and also allow the user to submit data. The data submission platform will be a critical component of future testing of the RUSI model.

Although this research is on-going, it is our hope that cities might begin to use the RUSI model as a way to stratify there planting sites by quality. In doing so, city planners might better identify high-quality and low-quality planting sites. City planners might utilize this information to better match species tolerances to sites conditions. We would encourage city planners to diversify their urban forests by planting less common species (or species with low tolerances to urban stress) in their highest quality planting sites. Likewise, more efficient use of resources might be attained by planting known "tough" trees in the low-quality urban sites.

Research Team Participants and Students

- Michelle Catania, Soil Science Research Assistant, M.S. (Northern Illinois University)
- Corinne Erickson, B.S. (University of Michigan) – soil/tree fieldwork, analysis
- Miles Schwartz-Sax, Ph.D. in progress (Cornell University) – soil/tree fieldwork, soil analyses
- Victoria Colclasure, B.S. (Lewis University) – soil carbon analyses
- Chris Burns, B.S. (Butler University) – soil and tree fieldwork
- Kevin Garbis, B.S. (Northern Illinois University) – soil and tree fieldwork
- Jason Maruszak, B.S. (Eastern Illinois University) – soil laboratory analyses
- Christina Fites (Indiana University South Bend) – Undergraduate Research Fellow
- David Carter (University of Maine) – RUSI analyses in New York and Ithaca

Significant progress has been made during the time of this grant, but research will continue to answer unresolved issues after the completion of this grant.

This report was prepared by:
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Signature of Authorized Official ______________________ Date May 9, 2015