2019 ANNUAL REPORT

HTIRC
HARDWOOD TREE IMPROVEMENT & REGENERATION CENTER

PURDUE UNIVERSITY | Forestry and Natural Resources

ABOUT HTIRC

The Hardwood Tree Improvement and Regeneration Center (HTIRC) was conceived in 1998 to address a perceived void in hardwood tree improvement research in the Central Hardwood Forest Region (CHFR) and is committed to enhancing the productivity and quality of CHFR trees and forests for the economic and environmental benefits they provide. Scientists at the HTIRC are using conventional tree improvement breeding as well as molecular and genetic technologies to improve the wood quality, growth characteristics, and insect and disease resistance of trees like black walnut, black cherry, red and white oaks, butternut and American chestnut. Research in tree breeding, tree nursery practices, tree plantation establishment and management, and Central Hardwoods silvicultural systems is aimed at increasing the regeneration success rate for high-quality hardwood trees and forests.

Our mission is to advance the science and application of tree improvement, management, and protection of hardwood forests, with emphasis in the Central Hardwood Forest Region.

John S. Wright Forestry Center

Hardwood Tree Improvement Center
Purdue University

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2019 HIGHLIGHTS

PERSONNEL

- Mark Coggeshall (Co-Director USDA Forest Service portion) announced his retirement effective February 14, 2020. We wish Mark the best in retirement!

RESEARCH

- HTIRC Executive Committee approved funding six new research proposals starting in 2020 that advance the goals of the HTIRC strategic plan (see table below).

PROJECT TITLE	PI	FUNDING	DURATION
Economic analysis of growth & yield and thinning decisions on hardwood plantations	Zhou	$ 96,417	2
Development of micropropagation and regeneration system for black walnut	Karve	$ 82,935	2
Precise quantification of forest disturbances with UAS	Hupy	$ 142,455	3
Using remote sensing to characterize stress epidemiology in hardwood forest stands	Couture	$ 162,759	3
A new, faster, cheaper, and easier way to measure HTIRC plantations	Shao	$ 149,000	3
Geo-referenced and image-assisted in-situ biometric evaluation tool for precision growth and yield modeling	Gazo	$ 149,891	3

OUTREACH/EDUCATION

- Proceedings from an International Union of Forest Research Organizations (IUFRO) Restoring Forests symposium in Lund, Sweden, co-organized by Douglass F. Jacobs, were published in the March 2019 issue of the New Forests journal.
- We are pleased to report that the long-awaited "Nursery guide for the production of bareroot hardwood seedlings" is in print and will be posted online at the RNGR site (www.rngr.net). Bob Hawkins (nursery manager at Indiana DNR state nursery in Vallonia, IN), a Purdue grad, wrote one of the chapters!

STAKEHOLDERS

AMERICAN CHESTNUT FOUNDATION: The goal of the ACF is to restore the American chestnut tree to our eastern woodlands to benefit our environment, our wildlife, and our society.

AMERICAN FOREST MANAGEMENT, INC.: the largest forest consulting and real estate brokerage firm in the United States.

ARBORAMERICA, INC.: is devoted to the development of genetically superior, intensively cultivated, fine hardwood plantings that are offered as a long-term investment opportunity.

DANZER FORESTLAND, INC.: focused on high quality timberland acquisition opportunities and environmentally responsible forest management for sustained yield of high quality saw and veneer logs.

FORGEY TREE FARM: a family farm in Rush County, Indiana planting selections from HTIRCs hardwood tree breeding program as part of their overall reforestation plan.

FRED M. VAN ECK FOREST FOUNDATION: supports our research program in hardwood tree improvement and regeneration efforts.

INDIANA HARDWOOD LUMBERMEN'S ASSOCIATION: a trade association whose members share a passion for creating the world's finest hardwood products and a determination to maintain the sustainable productivity of our nation's forest resources.

INDIANA FORESTRY AND WOODLAND OWNERS ASSOCIATION: IFWOA's mission is to promote good stewardship of Indiana woodlands.

NATIONAL HARDWOOD LUMBER ASSOCIATION: NHLA's mission is to serve members engaged in the commerce of North American hardwood lumber through education, promotion, advocacy, and networking.

NELSON IRRIGATION: recognized as a world leader in state-of-the-art water application products for agriculture and industrial applications.

STEELCASE, INC.: the global leader in office furniture, interior architecture and space solutions for offices, hospitals, and classrooms.

USDA FOREST SERVICE NORTHEASTERN AREA STATE AND PRIVATE FORESTRY: collaborates with states, other federal agencies, tribes, landowners, and other partners to protect, conserve, and manage forests and community trees across the 20 Northeastern and Midwestern states and the District of Columbia.

WALNUT COUNCIL: a science-based organization that encourages research, discussion, and application of knowledge about growing hardwood trees.

RESEARCH TEAM

LEADERSHIP AND STAFF

Matthew Ginzel | *Director (Purdue)*
Janis Gosewehr | *Administrative Assistant*
Lenny Farlee | *Sustaining Hardwood Extension Specialist*
Elizabeth Jackson | *Engagement Specialist*
Weston Schempf | *Research and Communications Coordinator*
Lydia Utley | *Data Analyst*
Nathan Hilliard | *Laboratory Manager*
Patrick O'Neil | *Genomics Laboratory Manager*

PROJECT SCIENTISTS

John Couture | *Entomology*
Songlin Fei | *Measurements & Quantitative Analysis*
Rado Gazo | *Wood Products and Industrial Engineering*
Brady Hardiman | *Urban Ecology*
Douglass F. Jacobs | *Forest Biology*
Michael Jenkins | *Forest Ecology*
Shaneka Lawson | *USDA Forest Service, Research Plant Physiologist*
Jingjing Liang | *Quantitative Forest Ecology*
Richard Meilan | *Molecular Tree Physiology*
Carrie Pike | *USDA Forest Service, Region 9 Regeneration Specialist*
Michael Saunders | *Forest Biology/ Ecology of Natural Systems*
Guofan Shao | *Forest Measurement and Assessment/GIS*
Keith Woeste | *USDA Forest Service, Molecular Geneticist*
Mo Zhou | *Forest Economics and Management*
Joseph Hupy | *School of Aviation and Transportation Technology, Purdue University*

POST-DOCTORAL RESEARCH ASSOCIATES

Jennifer Antonides
Indira Paudel
Rucha Karve

GRADUATE STUDENTS

Molly Barrett | *MS*
Andrea Brennan | *PhD**
Sara Cuprewich | *MS**
Aziz Ebrahimi | *PhD*
Sayon Ghosh | *PhD*
Bradley Graham | *PhD*
Scott Gula | *MS*
Madeline Montague | *MS**
Alison Ochs | *MS*
Brande (Bee) Overbey | *PhD*
Minjee (Sylvia) Park | *PhD*
Sarah Rademacher | *MS*
Ben Rivera | *MS*
Kelsey Tobin | *PhD*
Rebekah Dickens Ohara | *PhD*
Geoffry Williams | *PhD**
Recep (Rich) Yildiz | *MS*

* *van Eck Scholar*

TECHNICAL STAFF

Brian Beheler | *Farm Manager*
Don Carlson | *Forester*
Caleb Kell | *Research Forestry Technician*
James McKenna | *USDA Forest Service, Operational Tree Breeder*
Caleb Redick | *Research Assistant*
James Warren | *USDA Forest Service, Biological Scientist/Operational Tree Breeder*
David Mann | *Research Assistant*

DIRECTOR'S REPORT

This year has brought continued growth and change to the HTIRC, and our 2019 Annual Report details many of the ways the Center has worked to deliver on our mission of advancing the science and application of tree improvement, management, and protection of hardwood forests.

Through our project-based funding model, we have continued to support the first round of projects and also funded an additional six projects this year – bringing the total number of projects to 13. In this Annual Report, we share first-year progress reports on projects already underway and summaries of the newly funded projects. The HTIRC Executive Committee reviewed and selected each of these for funding, and a special thanks goes to them for their vision and continued leadership and engagement. These key research projects directly serve our strategic research objectives and also reflect our commitment to serving the needs of our stakeholders. We have allocated ~$750,000 over the next three years to support the six new projects, and we anticipate funding additional projects in the coming year. Thankfully, funding from the Fred M. van Eck Forestry Foundation continues to be strong, and we anticipate funding additional research projects in 2020.

We remain steadfast in our commitment to connect our partners, collaborators, and stakeholders with the people, information, and products of the center. This Annual Report details many of the ways we have engaged stakeholders in the past year and delivered educational programs and extension products to a broad audience. I greatly appreciate the efforts of our advisory committee, staff, project scientists and students in supporting and conducting cutting-edge research that is relevant to our stakeholders.

In closing, I want to personally thank Mark Coggeshall for his service to the HTIRC over the past three years. By the time this Annual Report is published, Mark will have retired from his position as Project Leader of NRS-14 and Co-Director of HTIRC. He arrived at a critical time for the Center and it was a pleasure to work with him over the past few years to chart a new course for the HTIRC. We wish Mark the very best in his retirement!

Group talking about the HTIRC select black walnut breeding program.

Matthew Ginzel
HTIRC Director

HTIRC
HARDWOOD TREE IMPROVEMENT
& REGENERATION CENTER

MISSION AND ORGANIZATION

The mission of the HTIRC is to advance the science and application of tree improvement, management, and protection of hardwood forests, with emphasis in the Central Hardwood Forest Region (CHFR). We seek to develop research and technology-transfer programs that provide knowledge focused on the establishment and maintenance of sustainable, genetically diverse native forests and the development of highly productive woodlands that provide a wide array of products and services.

HTIRC'S STRATEGIC PLAN ARTICULATES DIRECTIONS TO:

- Produce hardwood trees with desirable traits, using both classical tree breeding and novel tree improvement techniques.
- Improve management strategies and techniques to enhance the ecological sustainability and economic benefits of hardwood forests.
- Develop and demonstrate strategies to address existing and emerging threats to hardwood forests.
- Engage stakeholders and address their needs through communicating research findings and management recommendations.
- Educate future leaders in tree improvement, management, and protection of hardwoods.

Our research and development objectives are centered on the improvement, management, and protection of hardwoods in the CHFR. These objectives represent a balanced portfolio that includes low-risk projects that will provide short-term incremental gain and higher-risk projects that could lead to rapid and significant innovation.

We are also committed to connecting our partners, collaborators, and stakeholders with the people, information, and products of the HTIRC through our technology-transfer efforts. Our plan articulates a pathway by which we will engage a broad audience to explain the benefits of forest research, management, and tree improvement for people and the environment.

EXECUTIVE COMMITTEE

To help us deliver on our strategic objectives, a HTIRC Executive Committee was formed from members of our existing Advisory Board. Duties of the Executive Committee include the timely oversight of all HTIRC activities, as well as providing input to the FNR Department Head and HTIRC leadership in the form of recommendations as they relate to annual research budget allocations. The membership of the Executive Committee is as follows:

- Guillermo Pardillo *(ArborAmerica)*
- John Brown *(Pike Lumber)*
- Lee Eckart *(Danzer)*
- Dan Dey *(USDA Forest Service)*
- Jennifer Koch *(USDA Forest Service)*
- Jack Seifert *(Indiana DNR)*

UPDATE – CENTER FOR ADVANCED FORESTRY SYSTEMS

The HTIRC at Purdue University, along with Oregon State University, co-founded the only forestry-based National Science Foundation (NSF) Industry/University Cooperative Research Center (I/UCRC). The NSF I/UCRC Center for Advanced Forestry Systems (CAFS) was established in 2006 to address challenges facing the wood products industry, landowners, and managers of the nation's forestland. CAFS originally included North Carolina State University, Oregon State University, Purdue University, and Virginia Tech. Since then, CAFS expanded to nine distinct university sites that include the above in addition to: Auburn University, University of Georgia, University of Idaho, University of Maine, and University of Washington.

HTIRC Purdue has been part of CAFS during Phase I (2006-2011) and Phase II (2012-2017). At the end of 2019, NSF awarded our Phase III CAFS proposal, which will continue our involvement with CAFS until 2024. CAFS couples support of HTIRC partners with investments from NSF to support research projects that aim to solve complex, industry-wide problems. In addition to the funding support from NSF for CAFS, there is opportunity to apply to NSF for supplemental grants that support fundamental research and research experience for undergraduate students.

A CAFS Industrial Advisory Board (IAB) reviews ongoing and completed activities and selects new projects. In addition, the IAB provides input to NSF on the functioning of the Center. The IAB strongly influences the priority given to various research projects. Each university site appoints a representative to the IAB, which provides direction to CAFS's operation and research activities. Guillermo Pardillo, member of the HTIRC Executive Committee, will serve as our representative to the IAB.

In CAFS Phase III, HTIRC Purdue has proposed to pursue new collaborative research initiatives with partners across CAFS university sites, including: 1) Using hyperspectral imaging to evaluate forest health risk, and 2) Improving efficiency and accuracy of enhanced forest inventories derived from LiDAR. These themes align with current HTIRC funded projects, such as 1) Characterizing abiotic and biotic stress using hyperspectral information; 2) Using remote sensing to characterize stress epidemiology in hardwood forest stands; and 3) Using terrestrial laser scanning to assess tree health and quality. Support from CAFS will go to support projects that address these themes as part of our project-based funding model.

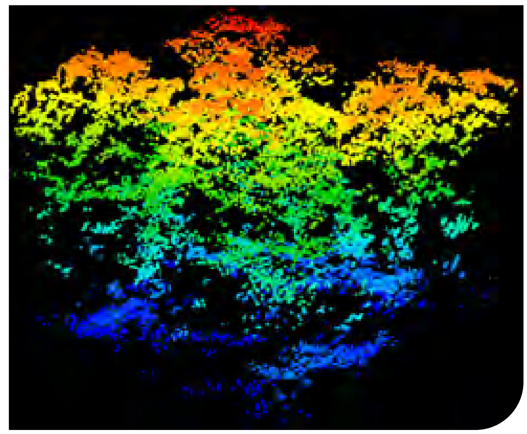
CAFS website: https://www.iucrc.org/center/center-advanced-forestry-systems

INTEGRATED DIGITAL FORESTRY INITIATIVE (IDIF)

Advancements in digital technology have revolutionized society and daily life. Smartphones today put more computing power in our pockets than the computer on board with the Apollo Mission. Yet studying and managing forest resources still primarily relies on antiquated, imprecise, and tedious tools like sticks and tape measures. These manual methods are costly in terms of time and labor and are inherent sources of error. More importantly, reliance on such traditional methods prevents us from taking full advantage of the critical services that forests provide (e.g., clean water, timber, fiber, and fuel) and limits our ability to minimize public hazards, such as forest fire and pest outbreaks.

The overarching goals of Purdue's **iDiF Initiative** are:
(1) to revolutionize forestry with an effective digital system for precision forest management that maximizes the social, economic, and ecological benefits of urban and rural forests, and (2) building a globally competitive next-generation workforce for the information age. The **iDiF Initiative** will harmonize four key components of digital age technology – Internet of Things (IoT), Big Data, Artificial Intelligence (AI), Edge and Cloud Computing – to advance the following thrusts:

- AI-assisted tree inventory with multi-platform and multi-scale remote sensing data
- IoT, Big Data, and Edge and Cloud Computing-enabled precision forest management and optimization
- Large-scale forest health (fire, disease, disturbance) monitoring and mitigation
- Digital technology-savvy interdisciplinary workforce education (undergraduate and graduate)

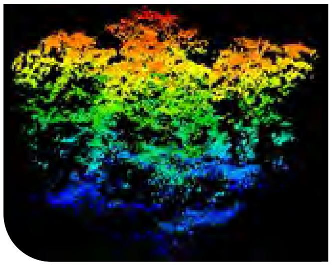


Example of 3D forest stand from aerial LiDAR. Color represents height of LiDAR points.

Forests support more than 11 million jobs (one of the major employment opportunities in rural America) and over $77 billion in timber-based products across the U.S. economy. Forests also provide vital ecosystem services, including flood control, nutrient management, and recreational amenities. The major impacts of digital forestry include, but are not limited to:

- Improved data and tools for management decisions and policy making
- Enhanced forest sustainability for timber & biomass supply, non-timber products, wildlife and recreation, water supply, and carbon sequestration, etc.
- Economic growth from timber as well as investment companies and small landowners
- Forest risk reduction (e.g., fire & disease outbreak) and mitigation (e.g., landslide & flood mitigation)
- Sustainable workforce development and employment in rural America, narrowing the digital divide
- Educated workforce for the information age

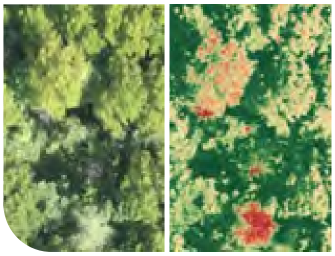
Purdue's multidisciplinary research team consists of over a dozen faculty members from various nationally ranked programs (Forestry and Natural Resources, Computer Graphics Technology, Electrical and Computer Engineering, Aviation Technology, Environmental and Ecological Engineering, Civil Engineering, and Information Studies) across four colleges. The team has six ongoing digital forestry-related projects (see next page for details). The team is supported by Purdue Research Computing that offers world-class cloud computing and a network of supercomputers optimized for GPU-based applications such as Machine Learning.



3D structure from aerial LiDAR

AERIAL TREE INVENTORY WITH LIDAR AND UAS IMAGES

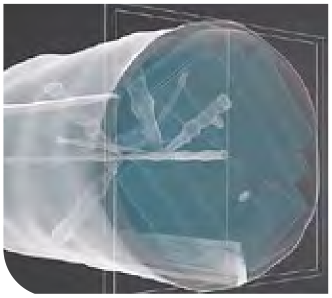
- AI-assisted automation of individual tree recognition and delineation
- Remote measurement of biometrics (size, biomass) in planted and natural forests



Pair of forest images showing stress early detection (red color)

MONITOR STRESS EPIDEMIOLOGY

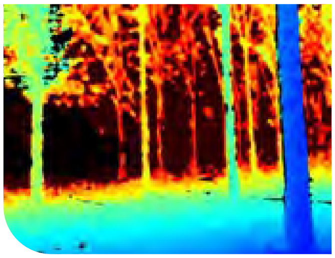
- Detection and tracking pest insect and pathogen incidence with machine learning on multi-temporal data
- Monitoring drought symptoms with multi-sensor platforms



Glass-view log from CT-scanning

PRECISION MANAGEMENT

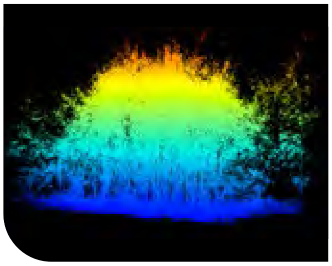
- Geo-referenced and image-assisted biometric evaluation for precision tree growth and yield modeling
- Log and lumber processing optimization with CT scanning



Digital depth view from LOGS

AUTOMATED TREE INVENTORY WITH PHOTOGRAMMETRY

- Low-cost Optical Gauging System (LOGS) with stereo cameras and machine learning for speedy automated tree measurement



Terrestrial LiDAR for tree structure

TREE HEALTH & QUALITY ASSESSMENT WITH LiDAR

- Ground-based LiDAR for precision tree structure characterization
- Analytical framework to assess quality and health of hardwoods on LiDAR data

Detection of fire disturbance (dark colored squares)

UAS DISTURBANCE DETECTION

- Feature-based high-resolution classification on multi-temporal data for planned and unplanned disturbance (fire, wind-throw, and logging)

IMPROVING ESTABLISHMENT PRACTICES OF PURE AND MIXED HARDWOOD PLANTATIONS BY REFINING SOIL SUITABILITY INDICES FOR BLACK WALNUT

PRINCIPAL INVESTIGATOR:

- **Shaneka Lawson**, *Research Plant Physiologist, Hardwood Tree Improvement & Regeneration Center (HTIRC), USDA Forest Service (USDA-FS), Northern Research Station (NRS), Department of Forestry and Natural Resources (FNR), Purdue University, (765.808.8188; shaneka.s.lawson@usda.gov)*

ABSTRACT

Black walnut forestry within the Central Hardwoods Region (CHR) has progressed primarily based on studies of trial and error among plantations. Although black walnut wood has been used for everything from gunstocks in the Revolutionary War to the finely crafted furniture of today, gaps exist in our knowledge base regarding the most efficient methods of growing this prized wood. Increased temperatures, insect pests, and numerous issues regarding planting site suitability have hindered our ability to consistently produce the most desirable nuts, lumber, and veneer. While considerable information regarding walnut growth remains anecdotal, researchers at the Hardwood Tree Improvement and Regeneration Center (HTIRC) have collected data regarding growth and performance of walnut families placed into both plantations and seed orchards. Remiss in those data were comprehensive soil studies to evaluate whether nutrient accumulations or other soil characteristics assisted with the observed superior growth of certain trees included in the study. As soils are composed of mixtures of clay, organic matter, sand, and silt, combinations of these materials can lead to a pH-balanced, nutrient-rich environment across or in pockets of a site. Superior trees planted in shallow, nutrient-poor soils likely demonstrate poor growth and may be removed from a breeding program unwittingly. We propose to: (1) Test the framework of the Wallace & Young (NRCS) black walnut suitability index at three black walnut planting sites, (2) Intensively sample soils at three black walnut and three Northern red oak sites, and (3) Investigate and analyze soil data in conjunction with planted black walnut family data to look for trends. Information gained from this proposal can increase planting success, help inform thinning decisions, and likely lead to greater economic values gained from timber stands and seed orchards.

YEAR 1 UPDATE

PROGRESS

This research project is on track. Thus far, 2 of the 6 proposed sites have been sampled completely (Figure 1). This means a sampling scheme has been created and soils were collected for each site, paying close attention to the spacing between samples and the genotypes of the trees on each site. The completed sites are both local, with one at Lugar Farm and the other at Throckmorton Purdue Agricultural Center (TPAC). A sampling scheme has been created and work has begun at the two sites in Michigan. A sampling scheme has been created for the final two sites, and sampling will be initiated next year.

All collected samples have been dried, sorted, and stored in preparation for shipment to undergo professional analyses. I have had several meetings with the soil experts to determine which analyses we would like to complete and how we can maximize the budget for each sample, as pricing obtained while writing the grant has changed. I have also met with the originator of the current soil suitability index for black walnut, Dr. Doug Wallace, to obtain his advice on how best to sample and which data to collect to mirror the information needed for the index.

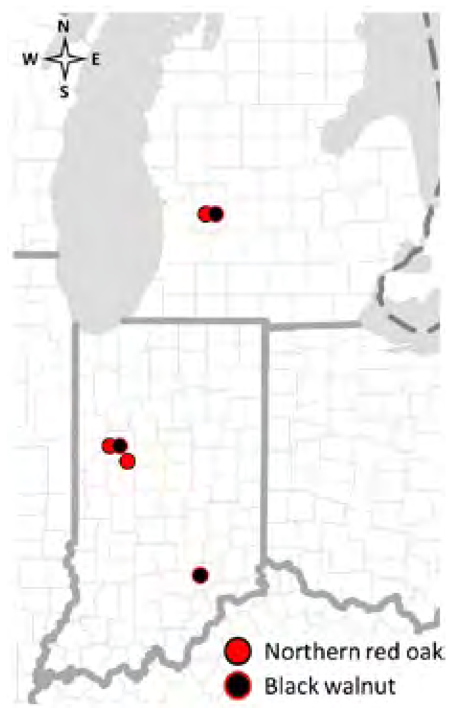


Figure 1. *Sample site locations*

OBSERVATIONS

Figure 2. *Soil color. (a) Brown and (b) grey-colored soils at a research site.*

Several interesting observations have been made at this point. During soil collection at each site, that according to the coarse soil maps published online are uniform, dramatic differences in soil texture, type, and color have been uncovered. For example, differences in soil color are the easiest to visualize (Figure 2a, b). It is obvious, visually, that significant differences in soil color, from warm brown to greyish-white, exist. This indicates this project is likely to uncover significant differences in the soil despite it being predicted to be uniform at a coarse scale.

Data has been collected thus far to indicate the depth of the “A” or “surface” layer and also the “B” layer to a depth of 76 cm (Figure 3). Samples were collected from approximately 0.3 m north of each tree across the site. To further visualize the data, I have created a reconstruction of the variation in depth of the “A” horizon to indicate how depths within a supposed homogeneous site undulated (Figure 4).

For the remainder of the year, the project will focus on the sites in Michigan. When unable to travel to Michigan (bad weather, other obligations), the focus will shift to the only remaining local site (Martell). This will allow for maximization of sample collection time. I plan to continue making progress in accordance to the schedule attached to the initial grant and to hopefully get ahead of schedule.

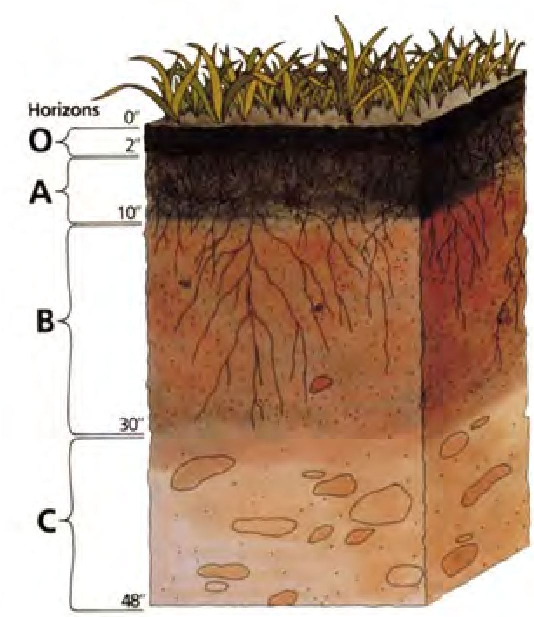


Figure 3. *Soil horizons.*

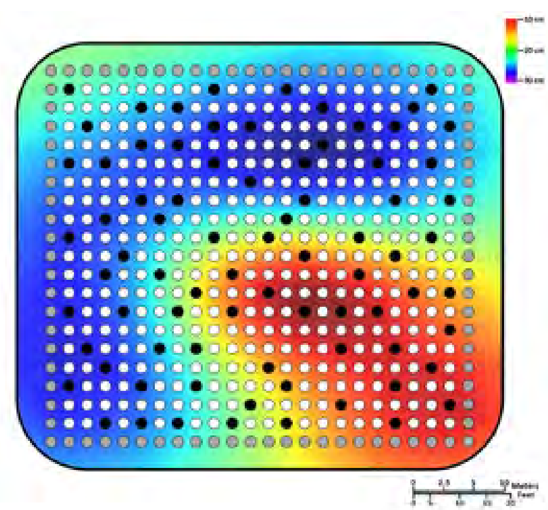


Figure 4. *Reconstructed data. Example interpolation of depth to the “A” horizon at the Lugar farm site. Black dots, sampled trees; grey dots, border trees.(dark colored squares)*

PROBLEMS

There are no major problems to report at this time, although weather conditions have not been ideal for continued collection. As the ground becomes drier, the difficulty in collecting soil samples grows exponentially. Also, if the soil becomes inundated with water, those areas with clay have been nearly impossible to sample down to our maximum depth of 75 cm.

The first trip to Michigan was meticulously planned to occur during a period of good weather. However, a sudden downpour on the second day forced a return to Indiana.

CHANGES PLANNED

News of this project and what it entails has spread extensively and, with a connection from the Forest Service, I have secured a Research Joint Venture Agreement (RJVA) with researchers at North Carolina State University. This RJVA will be for $80,000 over 3 years and will allow bioinformatics analyses of microbial communities at the Michigan sites.

Those sites were chosen because they are side by side and composed of black walnut on one site and Northern red oak on the other. These sites are the closest together of all the sites and are also the largest with greater than 2,000 stems per site. Thus, the samples to be collected from those two sites represent the highest numbers to be collected from individual sites and capture the largest number of families per site.

USING TERRESTRIAL LASER SCANNING TO ASSESS TREE HEALTH AND QUALITY (IDIF)

PRINCIPAL INVESTIGATORS:

- **Brady S. Hardiman**, *Assistant Professor, Forestry and Natural Resources, Purdue University, (bhardima@purdue.edu)*
- **Songlin Fei**, *Associate Professor, Forestry and Natural Resources, Purdue University, (sfei@purdue.edu)*

EXTERNAL COLLABORATORS

- **Ayman Habib**, *Professor of Civil Engineering, Purdue University*
- **Joey Gallion**, *Forest Inventory Program Manager, Indiana DNR*
- **Gord McNickle**, *Assistant Professor, Botany and Plant Pathology, Purdue University*

REPORT

ACCOMPLISHMENTS

- Objective 1 of our project is to develop a suite of tools including affordable, off-the-shelf TLS (terrestrial LiDAR systems) hardware and user-friendly analytical software that will ingest TLS data and output metrics of stand inventory and tree quality and health that are of interest and utility to both researchers and industry professionals.

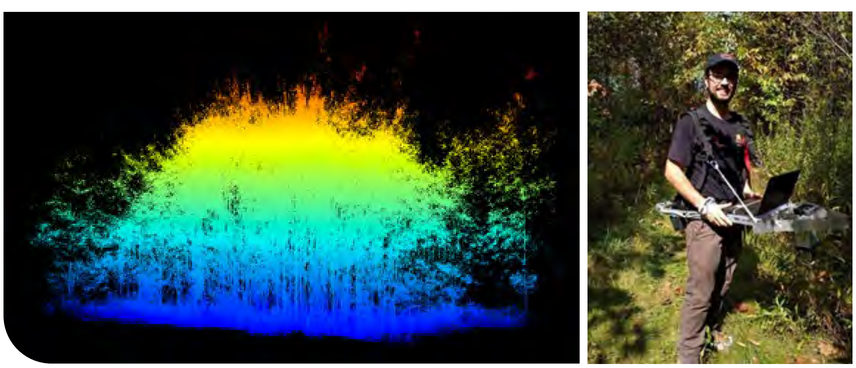


Figure 1. Left: 3D point cloud composed of 12 million individual data points acquired with a single scan using a terrestrial LiDAR system (TLS) in the center of a mixed species planted stand at Martell Forest; warmer colors correspond to taller portions of t the canopy. Right: FNR MS student Franklin Wagner using a portable canopy lidar (PCL) system, a type of TLS, to collect canopy structural data.

Substantial progress toward Objective 1 was achieved as part of recently graduated FNR Master's student Franklin Wagner's thesis research (co-advised by PIs Hardiman and Fei). Franklin's work focused on the comparison of terrestrial LiDAR systems (TLS) and aerial LiDAR systems (ALS) for characterizing forest structure. The field work for this project took place in mixed species plantations at Martell forest, in collaboration with Douglass F. Jacobs, John Couture, and Gord McNickle on a related HTIRC-funded project. TLS and ALS data acquisitions were collocated in plots varying in species composition and planting density (Figure 1). This design allows us to test the effect of diversity and competition gradients on development of tree- and stand-level structural features that contribute to tree health and quality. Pre-processing and analytical code were developed to extract and quantify structural features of interest. Results of this analysis demonstrate robust agreement between structural features derived from TLS and ALS across a range of stand composition and density. This work is currently in preparation for publication in a peer reviewed remote sensing journal. While this student was not funded by HTIRC project funds, the research advances generated though this project are essential to meeting our project objectives and represent substantial progress.

- Synergistic research: The research at Martell Forest conducted by Franklin Wagner during his MS thesis work was conducted in parallel with a similar study at a sub-continental scale (Figure 2) comparing the efficacy and compatibility of a different set of terrestrial and aerial (UAV) LiDAR systems for quantification of canopy structure. This study, also led by Franklin Wagner, leveraged ongoing terrestrial and aerial LiDAR data collection efforts at seven sites in the National Ecological Observatory Network (NEON) representing six different ecoclimatic domains. This work demonstrated statistically robust compatibility between aerial and terrestrially-derived metrics of canopy structure across a wide range of spatial scales and in diverse forest ecosystems. This work is in the final stages of preparation for publication, with submission for peer review anticipated during spring 2020. This work is highly complementary to the research described in the above bullet point and extends the applicability and relevance well beyond the Central Hardwood forest ecoregion to a wide array of other forest types and conditions.

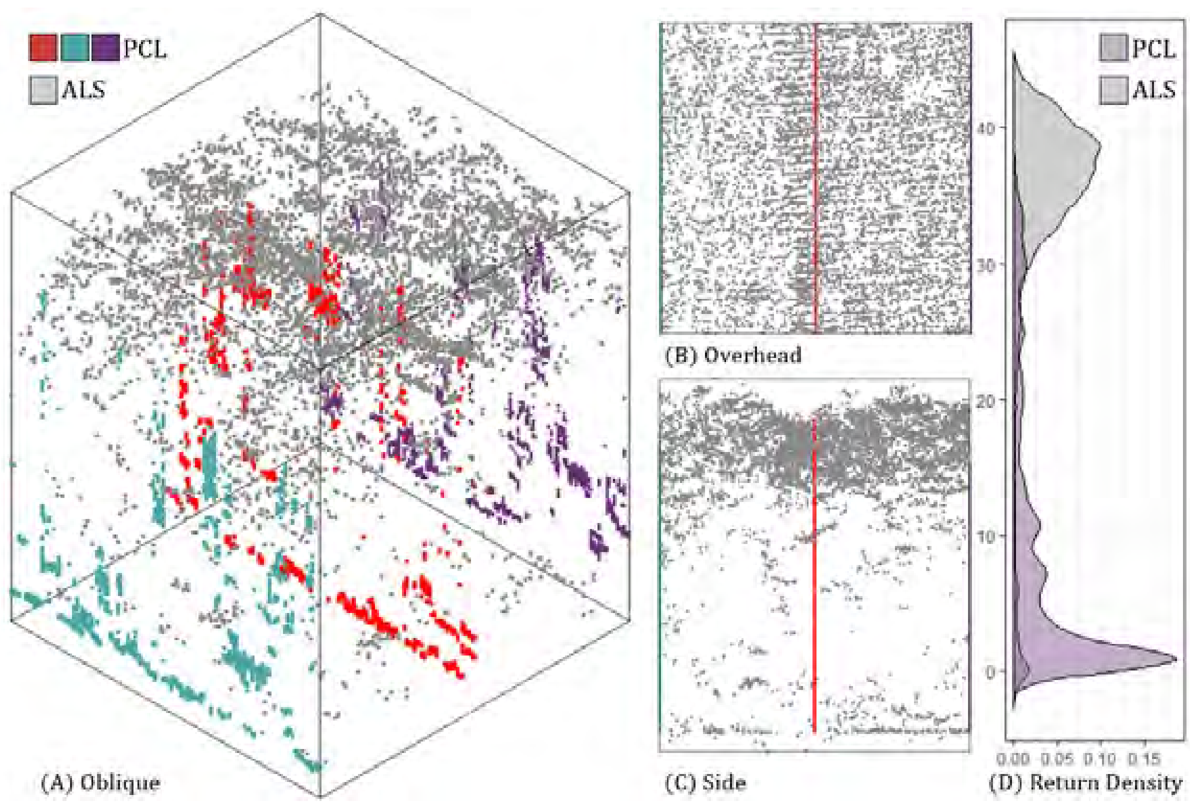


Figure 2. Comparison of ALS and TLS point clouds for Great Smoky Mountains plot GRSM_053 (40 x 40 m) from oblique (A), overhead (B), and side angles (C). Vertical profiles of return heights from raw LiDAR returns (D) demonstrate the occlusion experienced by both LiDAR methods as a result of their respective view angles.

ONGOING EFFORTS

- We are collaborating with Abdel Halloway, a postdoc in co-PI Gord McNickle's research group in Botany and Plant Pathology, to build a TLS processing workflow that can integrate a suite of computational tools to quantify tree and stand-level features indicative of tree health and quality from terrestrial LiDAR point clouds. Thus far, the workflow can, from an undifferentiated 3D point cloud, identify individual stems and estimate diameter, biomass, height, stem straightness, and taper. We are working to refine this workflow and will continue adding new functionality.

PLANNED WORK FOR 2020

- We will collect LiDAR data from additional HTIRC planted stands that represent a wider array of species, ages, tree health, and management conditions to test the workflow.

- We will begin to incorporate additional metrics of tree health and quality that are currently assessed using primarily qualitative or subjective methods (e.g., crown condition, bark condition, timber quality). We will develop and compare TLS-derived metrics for these tree characteristics against assessments produced using conventional methods.

NATURAL AND ARTIFICIAL REGENERATION GROWTH RESPONSE OF WHITE OAK ACROSS LIGHT AND UNDERSTORY COMPETITION GRADIENTS

PRINCIPAL INVESTIGATORS:

- **Mike R. Saunders**, *Associate Professor, Forestry and Natural Resources, Purdue University,* (*msaunder@purdue.edu*)

The lack of oak recruitment in eastern North America has been widespread and persistent over the past several decades. While there has been a plethora of research conducted on this issue, there exists significant gaps in our knowledge particularly concerning 1) natural regeneration of oak on mesic sites and 2) artificial regeneration of white oak (*Quercus alba*) in any context. White oak, in particular, is a foundational species, extremely important to wildlife, and has billions of dollars of economic value, particularly to the cooperage industry. Our project focuses on both natural and artificial regeneration of white oak.

At NWSC-Crane in southern Indiana, we are installing a replicated study of expanding group shelterwood systems, which has been used successfully to regenerate oak in Europe and within other forest systems in North America (Figure 1). This system creates a large amount of intra-stand heterogeneity that may create optimal light conditions for white oak regeneration (Figure 2). By combining these treatments with use of prescribed fire, we hope to identify an optimal suite of treatments that might allow natural regeneration of white oak on mesic sites.

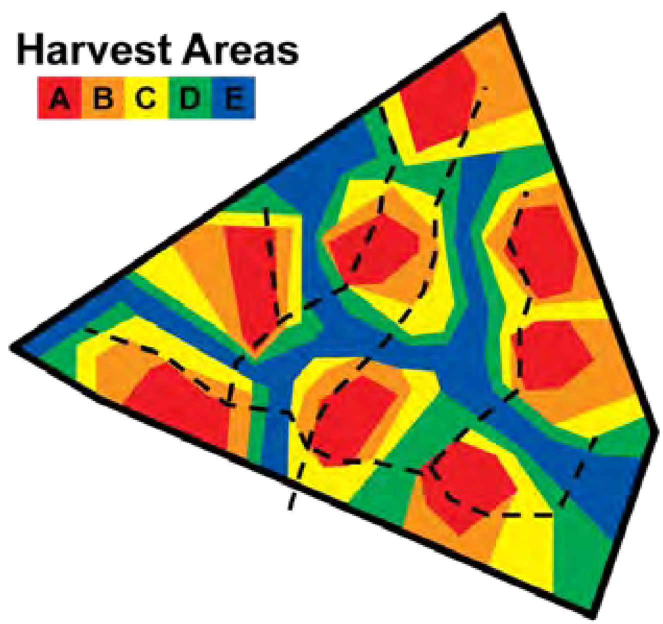


Figure 1. Expanding group shelterwoods are harvested over multiple entries (i.e., cutting cycle); each harvest area is on a different schedule, moving outward from A to E. Initial entries in an area typically are establishment cuts that remove 50% of the overstory basal area. Second entries remove most of the remaining overstory. Midstory removal operations can be used ahead of establishment cuts to help build more advanced oak regeneration before the overstory harvesting begins. This study uses a 10-year cutting cycle.

Figure 2. A view across the midstory removal area into the group opening.

This is a long-term endeavor. HTIRC funds are funding a new graduate student, Molly Barrett, who will be measuring the regeneration response across the first two replicates of this study. This will occur in summer 2020. HTIRC funds, however, were leveraged for a successful Cooperative Ecosystem Studies Unit proposal for $489,189 over the next 5 years. This will expand the study to four replications and expand the underplanting experiment (described below) to additional sites.

In at least four of the expanding groups, we will install an underplanting of white oak that test different levels of weed control. These will extend from the gap center into the adjacent, intact forest. Four different seed sources will be used in the planting (Figure 3). Seed was collected this fall from Illinois (1,970 acorns), Indiana (2,550 acorns; Figure 4) and Arkansas (1,778 acorns); all were planted at Vallonia State Nursery. A region-wide white oak mast failure prevented collection of acorns from a more northern seed source. Therefore, we have an agreement with the Wisconsin DNR to obtain 1,000 2-0 bareroot stock from their Griffith State Nursery.

This study will be planted in spring 2021 with growth and survivorship measurements taken in early fall 2021.

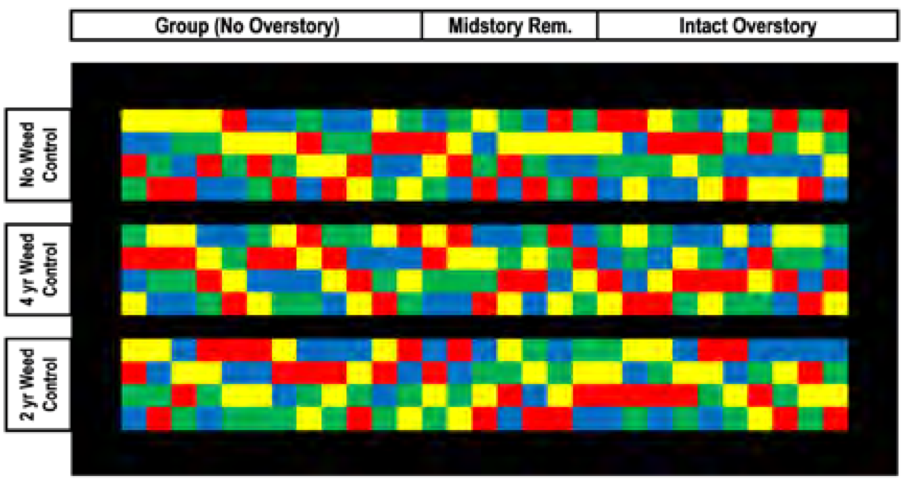


Figure 3. Schematic of the underplantings. Each color is a different seed source. Black cells are either planted to red or black oaks to buffer against edge effects. Each cell is 2 m x 2 m.

Figure 4. A sample of the scarce fall 2019 collections for white oak in Indiana.

PRODUCTIVITY-DIVERSITY RELATIONSHIPS IN HARDWOOD PLANTATIONS

PRINCIPAL INVESTIGATORS:

- **Douglass F. Jacobs (PI)**, *Fred M. van Eck Professor of Forest Biology, Department of Forestry and Natural Resources, Purdue University, (djacobs@purdue.edu, (765) 494-3608)*
- **John Couture (Co-PI)**, *Assistant Professor, Entomology, Purdue University*
- **Lenny Farlee (Co-PI)**, *Extension Forester, Forestry and Natural Resources, Purdue University*
- **Brady Hardiman (Co-PI)**, *Assistant Professor, Forestry and Natural Resources, Purdue University*
- **Gordon McNickle (Co-PI)**, *Assistant Professor, Botany and Plant Pathology, Purdue University*

SUMMARY OF PROJECT GOALS AND ACCOMPLISHMENTS IN 2019:

Productivity and species diversity are correlated, but the mechanistic causes of the productivity-diversity correlation remain unresolved. Mixed species plantations should be more economically productive than single species plantations, but it is currently not possible to predict how many (and which) species should be planted to maximize timber production and economic value. Indeed, the productivity-diversity relationship shows that the same number of species can produce very different production outcomes, suggesting the importance of selecting compatible species and applying effective management. Rigorous field experiments are needed to examine mechanisms supporting this relationship. Using a 13-year-old experiment of three fine hardwood species planted as monocultures and species mixtures at varying densities, we are characterizing the productivity-diversity relationship over three growing seasons by studying functional, chemical, and structural traits, as well as above- and below-ground productivity. An improved understanding of the productivity-diversity relationship in mixed hardwood stands will generate plantation management advice; we will disseminate findings to landowners in the Midwest with extension field days and programs.

Measuring DBH in mixed species stands.

In 2019, four HTIRC graduate students focused their research on this project: Kliffi Blackstone (PhD, McNickle) is evaluating leaf litter, tree growth, dendrochronology, and physiological traits. Madeline Montague (MS, Jacobs) is studying belowground processes. Taylor Nelson (MS, Couture) is examining canopy processes. Franklin Wagner (MS, Hardiman/Fei), who defended his MS in July 2019, studied aerial and terrestrial LiDAR systems to quantify forest structure and function. Below, we summarize our specific accomplishments in 2019 related to the project objectives.

NET PRIMARY PRODUCTIVITY

Kliffi Blackstone (PhD, McNickle) is estimating net primary productivity (NPP) required for the productivity-diversity relationship within our experimental plots. We are partitioning NPP into leaves, stems and roots. For contemporary stem growth, we have taken measurements of tree diameter at breast height (DBH) in 2017, 2018 and 2019.

To estimate growth back to the initial planting date in 2007, we took basal wood cores from three trees of each species per plot, and we are using dendrochronology to estimate NPP. We completed all of the dendrochronology for the 1m and 2m plots in 2019, and the 3m plots will be completed next. We calculated the area of each tree ring as a basal area increment (BAI) and used this to estimate the productivity-diversity relationship. Interestingly, the relationship was negative and relatively flat, compared to the common positive correlation. This phenomenon was also seen in the leaf litter, which was collected via simple litter traps.

Leaf litter traps beneath mixed species stands.

We will continue to estimate productivity using DBH and litter traps. It is possible that the productivity-diversity relationship may change through time. These results deviate from our initial hypotheses, but we believe that they provide important insight into the development of mixed species forest plantations. Specifically, we think we can develop methods to identify species mixtures for which we would expect a positive diversity productivity relationship, or a negative/absent diversity productivity relationship. In other words, while this result was unexpected, we believe we can use it to develop recommended species mixes that would increase timber production, as well as non-recommended species mixes that would reduce timber production.

ROOT PRODUCTIVITY AND NON-STRUCTURAL CARBOHYDRATE STORAGE

Madeline Montague (MS, Jacobs) is evaluating the effects of competition on root productivity and non-structural carbohydrate (NSC) storage. Competition is intensified in plots with higher planting density. In addition, ecological theory suggests that trees growing in monoculture plots experience more competition than trees growing in mixture with other species due to the variation between species in resource requirements and acquisition strategies. Root productivity is an often-overlooked component of a comprehensive productivity budget, which our group will use to test the productivity-diversity relationship in our plantation experiment. NSC reserves are stored sugars that a tree draws from to fuel normal metabolic functions and energy-intensive processes like reproduction, defense against pests, and regrowth following disturbance. NSC reserves represent the balance between carbon supply (from photosynthesis) and demand; they indicate a plant's capacity to respond to and recover from damaging agents and environmental change.

Mesh ingrowth cores

Ingrowth core incubating in the field.

Roots and mycorrhizae extracted from ingrowth cores.

The main objective of this work is to assess belowground productivity and root allocation patterns across our competition experiment. Belowground productivity rates are quantified by isolating a single year of root growth using polypropylene mesh ingrowth cores. The ingrowth core method involves five steps: (1) extract a cylindrical core of soil 7.5 cm across and 50 cm deep using a soil corer; (2) remove the original roots from the soil sample; (3) place the ingrowth core into the hole and fill it with the same (root-free) soil that was extracted from that location; (4) allow one full year of root growth; (5) retrieve the ingrowth containing roots produced in exactly one year. Soil is extracted in sections from 0-10 cm, 10-30 cm, and 30-50 cm so that root system stratification by depth can be evaluated. 112 ingrowth cores were installed in October-December 2018 and were retrieved at the same time in 2019. Root samples were extracted from soil, weighed and ground with liquid nitrogen. We are currently working on extracting genomic DNA using Qiagen kits. Our next step will be to quantify the proportion of roots from each species in each soil core layer using quantitative PCR. These findings will be presented at the International Union of Forest Research Organizations (IUFRO) Mixed species forests: risks, resilience, and management conference during 2020 in Sweden.

A second vein of research is monitoring NSC dynamics in American chestnut (*Castanea dentata*) trees in our competition experiment. Though carbohydrate reserves could be especially important for American chestnut, as it is a prolific re-sprouter and threatened by the chestnut blight fungus, NSC dynamics have yet to be studied in mature *C. dentata*. Madeline is tracking NSC concentrations throughout the tree (leaves, branches, bole, and roots) to characterize seasonal NSC dynamics. Field sampling started in spring 2019 and is ongoing. In summer 2019, Madeline excavated and weighed eight chestnut trees to build an allometric model that will be used to convert NSC concentration to total pool size. Our experimental design allows us to explore the degree to which competition mediates the relationship between productivity and NSC reserve accumulation.


Excavating a chestnut stump

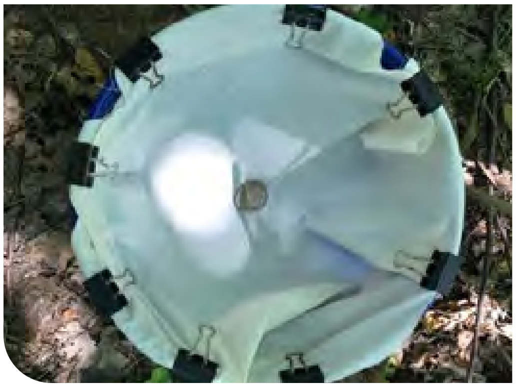

Excavated chestnut stump


Collecting leaf and twig samples for nonstructural carbohydrate (NSC) analysis.

CANOPY PROCESSES

To determine the influence of biodiversity and competition on nitrogen resorption efficiencies (NRE), Taylor Nelson (MS, Couture) collected midseason green-leaf samples in addition to weekly senescent leaf material. All samples were flash frozen, freeze dried, and milled into powder before being tested for nitrogen content via combustion reaction, after which NRE was calculated. Our findings suggest that as diversity increases, trees become less efficient at resorbing nitrogen during senescence, and more so when competition (i.e., plant density) decreases. These responses, however, vary among species. These outcomes suggest that trees adjust physiological process to conserve foliar nitrogen, opposed to losing it in leaf litter, when in the presence of other individuals who take up soil nitrogen in a similar manner. These findings will be presented at the International Union of Forest Research Organizations (IUFRO) Mixed species forests: risks, resilience, and management conference during 2020 in Sweden.

Using pole pruners to collect foliar samples.



A bucket trap used to collect frass and other debris.

To estimate the influence of biodiversity and competition on canopy chemical profiles and insect feeding behavior, we are measuring the transfer of insect mediated materials from the canopy to the forest floor to examine the influence of patterns of canopy feeding on nutrient cycling. In 2018 and 2019, we collected foliar tissue at three time points (June, August, and October) and all samples are flash frozen, freeze dried, and milled into powder and stored for further chemical analyses. To assess canopy damage, we image the October foliar collections and calculate the percent missing tissue. Insect material fluxes (frass, or fecal material, and green leaf material produced from incompletely consumed leaf material) are collected monthly from May to October. Preliminary results from 2018 suggests that patterns of canopy damage, while low (although characteristic of damage levels of endemic insect herbivore populations), vary among levels of diversity and competition. This work was presented at the 2019 Entomological Society of America conference in Missouri.

We are currently working on a manuscript for the foliar nitrogen resorption data. In the lab, all foliar samples have been fully processed and frass samples are being sorted and weighed for future analysis.

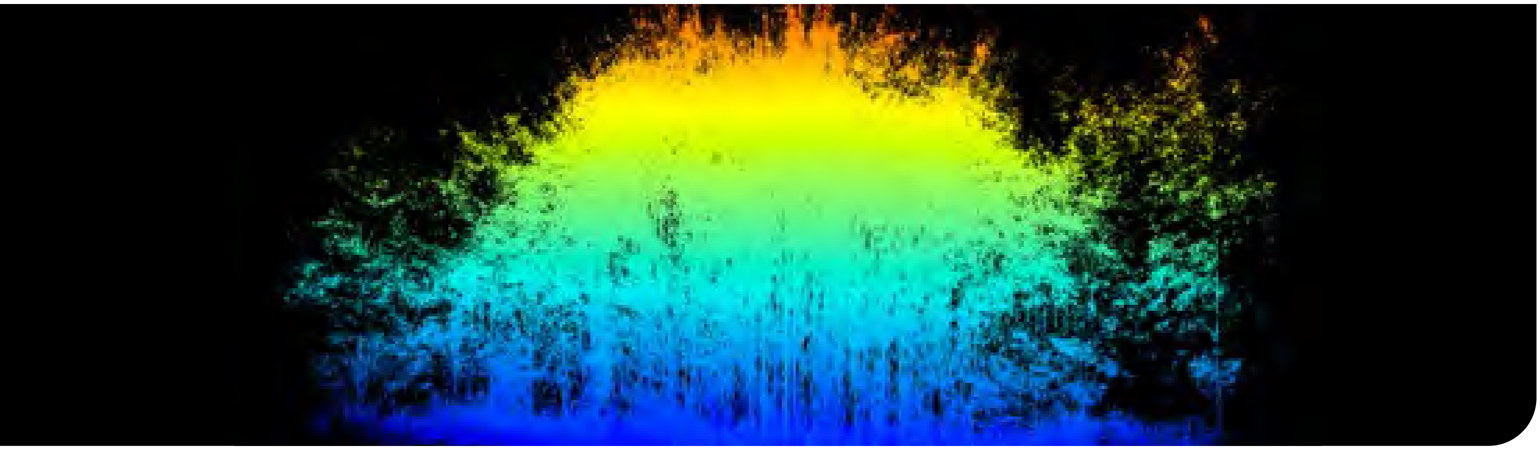
ENVIRONMENTAL EFFECTS

As part of his graduate research, Franklin Wagner (MS, Hardiman/Fei) collected data to characterize environmental effects on the hypothesized diversity-productivity relationship being studied in this project. In May 2019, we leveraged HTIRC funds to upgrade our network of dataloggers to a new model capable of uploading data in real time. Each solar-powered datalogger runs a suite of sensors that measure light, air temperature, relative humidity, volumetric soil water, and soil water potential at 5-minute intervals. These sensor clusters are located in the center of each plot in Block 4, where they have been running continuously since early June 2019. Measurements are uploaded to the cloud daily via cellular uplink and are available to all project researchers through a web interface.

Upgraded datalogger with sensor cluster.

In late fall 2019, the aboveground light sensors associated with each sensor cluster were collected and returned to the lab for storage over the winter to minimize potential damage. Soil sensors were left onsite to collect data over the winter because the greatest risk for damage to the sensors is associated with installation and removal. Light sensors will be re-deployed in spring 2020 prior to bud break. In summer/fall 2019, we used the Leica BLK360 terrestrial laser scanner (TLS) to acquire a second round of 3D LiDAR point clouds from the center of each of 63 plots in the study design. These high-resolution scans are being used to create digital reconstructions of stand structure, and quantify structural features that have been shown in previous work to drive stand level growth rates. This work is being led by Abdel Halloway, a postdoc in co-PI Gord McNickle's research group.

Setting up a terrestrial laser scanner to acquire scans at the center of each plot.



Terrestrial LiDAR data acquired from the mixed species stands.

UNDERSTANDING AND MANIPULATING PLANT-SOIL FEEDBACKS TO MANAGE THE INVASIVE SHRUB LONICERA MAACKII

PRINCIPAL INVESTIGATOR:

- **Michael Jenkins**, *Professor, Forestry and Natural Resources, Purdue University, (jenkinma@purdue.edu)*

EXTERNAL COLLABORATOR:

- **Pierre-Luc Chagnon**, *Université de Montréal, Institut de Recherche en Biologie Végétale, Montréal, Canada*

SUMMARY AND PROGRESS

After invasion, non-native plant species can change the structure and function of soil microbial communities, which may increase the productivity of the species while reducing the success of its competitors. In this project, we are using field-based and greenhouse studies to examine how feedback relationships between a non-native shrub (Amur honeysuckle – *Lonicera maackii*) and the soil influence invasion success in Central Hardwood Forests. In 2019, we completed our first field sampling in Indiana and began laboratory preparation and greenhouse experiments at the Université de Montréal. In October, we collected soils cores from multiple forest sites representing a range of invasion intensity and duration by honeysuckle (Figure 1). We subsampled these cores for chemical testing and are prepping the remaining soil to serve as inoculum for greenhouse experiments. During October fieldwork, we also collected fruit from mature honeysuckle shrubs (Figure 2). Seeds were extracted from the fruit, and were washed, dried, and refrigerated. We then treated them with gibberellic acid and are stratifying them at 4° C for twelve weeks (Figure 3). In late March, seeds will be germinated and inoculated with soil collected in Indiana. The resulting plants will be used in our greenhouse experiments to determine if soil microbial communities from older and more intense invasion are associated with greater growth and productivity of Amur honeysuckle seedlings.

Figure 1. *Collection site at Richard G. Lugar Forestry Farm near West Lafayette, Indiana.*

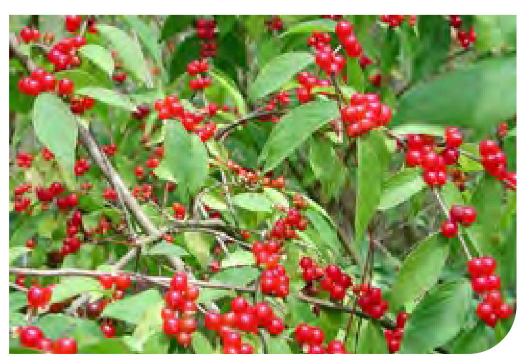


Figure 2. *Mature fruit of Amur honeysuckle.*

In 2020, we will collect plant roots and additional soil from a single site in Indiana. These samples will be used to characterize the sharing of pathogens between honeysuckle and native plant species. Hiba Benmohamed (PhD student in Chagnon's lab) will analyze the dataset and complete statistical analyses by March 2021.

Figure 3. *Amur honeysuckle seeds undergoing cold stratification.*

TREE INVENTORY WITH AERIAL REMOTE SENSING (IDIF)

PRINCIPAL INVESTIGATORS:

- **Songlin Fei**, *Associate Professor, Forestry & Natural Resources, Purdue University, (sfei@purdue.edu*)
- **Guofan Shao**, *Professor, Forestry & Natural Resources, Purdue University, (shao@purdue.edu)*

EXTERNAL COLLABORATORS:

- **Joseph P. Hupy**, Associate Professor, *School of Transportation and Aviation Technology, Purdue University*
- **Joey Gallion**, *Forest Inventory Program Manager, Indiana DNR*

ANNUAL REPORT

Objective 1. *Develop tools for automated detection and delineation of individual trees and measurement of biometrics for hardwood species using low-density aerial LiDAR. Tools developed from this objective can be applied at stand, landscape, and possibly state level using freely available aerial LiDAR.*

1. Progress has been made in delineating plantation trees with low-density LiDAR. We developed a point-density-based algorithm (PDM) to delineate trees. We demonstrated that the PDM-based approach produced an 89% detection accuracy to identify deciduous trees in our study area. The results have been published in International Journal of Remote Sensing (Shao et al. 2018).
2. Two areas of efforts are ongoing related to LiDAR-based tree delineation. The first is to test the aforementioned algorithm for plantations with other species and in different age. The second area is to test the delineation in natural stands. We had one NSF REU student on the project.

Objective 2. *Develop algorithms for automated detection and delineation of individual trees and measurement of biometrics for hardwood species using UAS orthophotos. Tools developed from this objective can be applied on the stand level and can be employed cheaply and as frequently as the user desires.*

We have recruited a postdoc to work on using orthophotos to delineate individual trees. Moreover, we have leveraged other resources to work on the project. One MS student from FNR advised by Dr. Shao, and one MS from Aviation Technology advised by our collaborator, Dr. Hupy, have been recruited to work on this area of reach. Multiset of orthophotos have been captured for various areas, including Martell and McCormick Woods, with a spatial resolution of sub-centimeter **(Figure 1)**.

More importantly, we are experimenting multiple algorithms to take the advantage of these high-res orthophotos. One such effort is to use a leaf-off image to delineate trees and measure stem DBH. Some preliminary analysis from a walnut plantation shows promising results. We are able to delineate trees with high accuracy and measure DBH from air with sub-inch accuracy **(Figure 2)**. We are in the process of publishing the findings and test out the algorithm in other plantation settings.

Figure 1. High-resolution UAS (left) and a sub-centimeter image captured in Martell Forest (right).

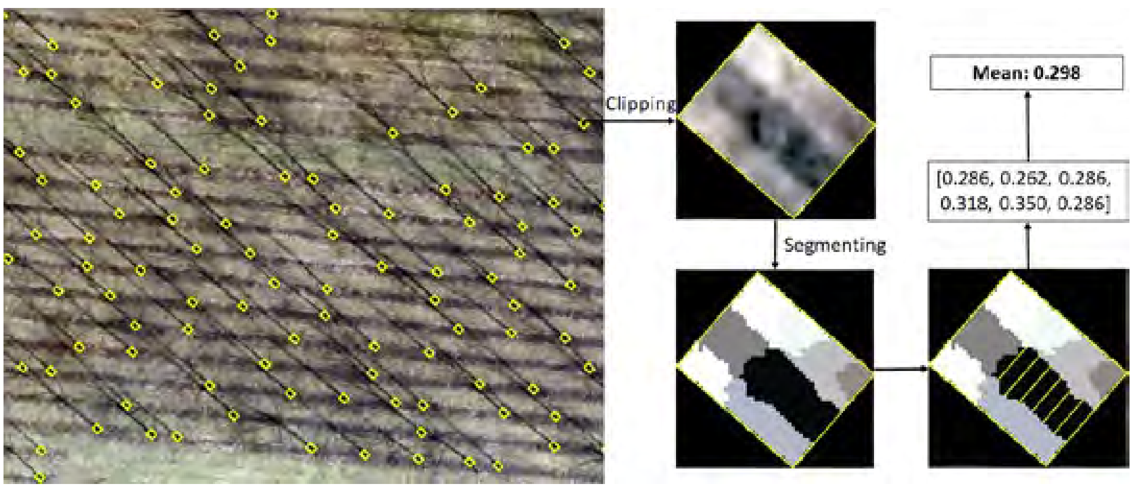


Figure 2. Delineation of individual trees in a Martell plantation with high-resolution UAS photo (left) and a sub-inch measurement of DBH (right).

Objective 3. *Disseminate tools to stakeholders and managers. We will coordinate with other iDiF projects to disseminate our developed tools and products to HTIRC stakeholders and other natural resource managers.*

The iDiF initiative has been taking root. We have recruited team members from various colleges across the campus. More importantly, we are making efforts to highlight our findings in various outlets. The following is a list of high-level activities related to the iDiF initiative.

- Microsoft – We introduced the integrated digital forestry initative to Microsoft on August 6, 2019. Our team met with a Microsoft leadership team to discuss possible collaborations.
- Digital Agriculture Round-table. On September 10, 2019, we presented “A bird’s eye view: digital forestry” to a group of stakeholders, business leaders, and news media about the iDiF initiative.
- Forbes Ag Tech Summit. We were invited to present iDiF at the 2019 Forbes Ag Tech Summit to various digital agriculture companies and potential investors at Indianapolis.
- FIA Annual Meeting. We were invited to provide a keynote presentation and several organized presentations at this meeting. We disseminated our research findings to over 300 managers, researchers, and practitioners.

ISSUES

The postdoc we recruited on the project is no longer with us due to document issues with the outbreak of the coronavirus as he traveled back to China during the winter break. We are actively recruiting a new postdoc/tech to work on the project.

CHARACTERIZING ABIOTIC AND BIOTIC TREE STRESS USING HYPERSPECTRAL INFORMATION (IDIF)

PRINCIPAL INVESTIGATORS:

- **John Couture**, *Assistant Professor, Entomology, Purdue University, (couture@purdue.edu)*
- **Douglass F. Jacobs**, *Fred M. van Eck Professor of Forest Biology, Forestry and Natural Resources, Purdue University*

We have three objectives in this proposal: 1) determine the ability of hyperspectral data to provide information related to tree status in response to abiotic and biotic stress, 2) assess the reliability of hyperspectral information to scale from leaf, to tree, to stand level measurements, and 3) evaluate the validity of hyperspectral data to characterize stress responses over different spatial scales in different geographic locations. We will collect data across a range of experiments, from controlled greenhouse to experimentally designed plots, by collecting hyperspectral information using different measurement approaches (contact, UAV, and possibly manned aircraft) along with biochemical and physiological reference data and diagnostics of tree stress.

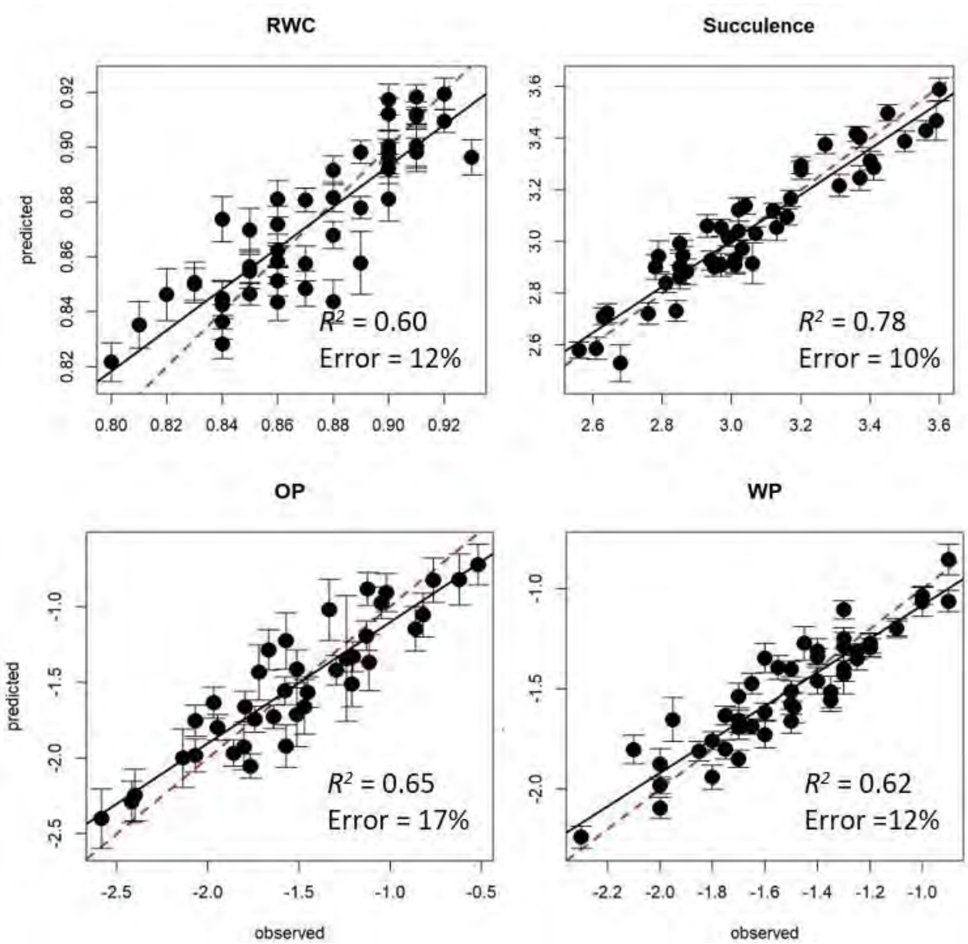


Figure 1. Observed vs predicted plant traits related with water status. RWC: relative water content; OP: osmotic potential; WP: water potential.

To date, we have recruited a graduate student, FNR PhD student Sylvia Park, MS, who started in June 2019, for the project and we have made progress addressing all three objectives. For objective one, determine the ability of hyperspectral data to provide information related to tree status in response to abiotic and biotic stress, we have conducted both greenhouse and field collections. For greenhouse collections, we have finished one experiment looking at the influence of nitrogen and water stress on black walnut (*Juglans nigra*) to develop spectral-based predictive models to estimate physiological and chemical responses to the stress environments. Preliminary outcomes of models developed suggest that spectral models can reliably estimate a number of black walnut responses to stress (Figures 1 and 2), even when plants show minimal visible symptoms. In addition, in a second experiment we found that leaf spectral data can accurately classify a black walnut sapling infected with *Geosmithia morbida*, causal agent of Thousand Cankers Disease, and that classification accuracy increased with length of infection (Figure 3). Additional, ongoing experiments have extended the first two experiments in relating hyperspectral data with tree stress. A third experiment includes modelling of stress responses of both black walnut and red oak (*Quercus rubra*) exposed to nutrient and salt stress, and a fourth experiment includes spectral classification of *G. morbida* and *Fusarium solani*, both inoculated singularly and together, while in the presence of water stress.

For objective two, *assess the reliability of hyperspectral information to scale from leaf, to tree, to stand level measurements*, we have acquired full-range hyperspectral at multiple measurement scales in 2018 and 2019. In 2018, we collected contact, leaf-level and unmanned aerial vehicle (UAV) images, and in 2019 we collected contact, leaf-level, UAV, and manned aircraft images (Figure 4).

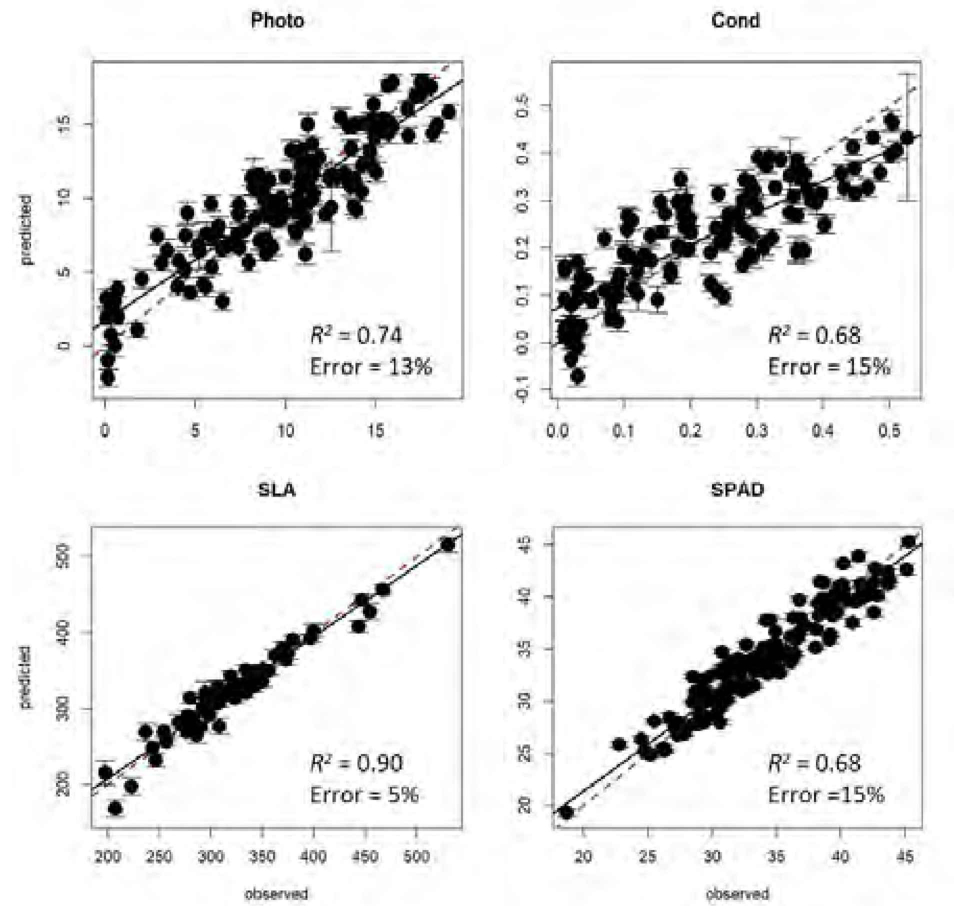


Figure 2. Observed vs predicted plant traits related with photosynthetic capacity. Photo: photosynthesis; Cond: stomatal conductance; SLA: specific leaf area; SPAD: chlorophyll

For objective three, *evaluate the validity of hyperspectral data to characterize stress responses over different spatial scales in different geographic locations*, we are utilizing data collected in objective two to examine that ability of hyperspectral data to classify insect and pathogen stress at leaf, UAV, and aircraft scales. We also have a collaboration with the University of Pisa, Italy, which is conducting parallel experiments examining hyperspectral characterization of biotic and abiotic stress in trees. Dr. Lorenzo Cotrozzi, former postdoc in the research group of Dr. Couture, is examining the influence of acute ozone exposure and water stress on *Quercus spp.*

Outputs: This grant facilitated the submission of a larger, grant proposal, titled “Advanced Deep Learning Framework for Remote Sensing-Based Monitoring of Forest Health,” to the Advanced Information System Technology section of NASA. While unsuccessful, this effort was critical in establishing a collaboration with the Forest Ecology and Remote Sensing Laboratory at the University of Wisconsin-Madison. In addition, this grant has facilitated the training of Ms. Park in incorporating technology with tree physiology. After concluding experiments this year, Ms. Park plans to summarize many of the greenhouse-based experiments in a review article for publication. Ms. Park is currently processing the 2019 collections and is planning an experiment related with insect stress in the 2020 field season.

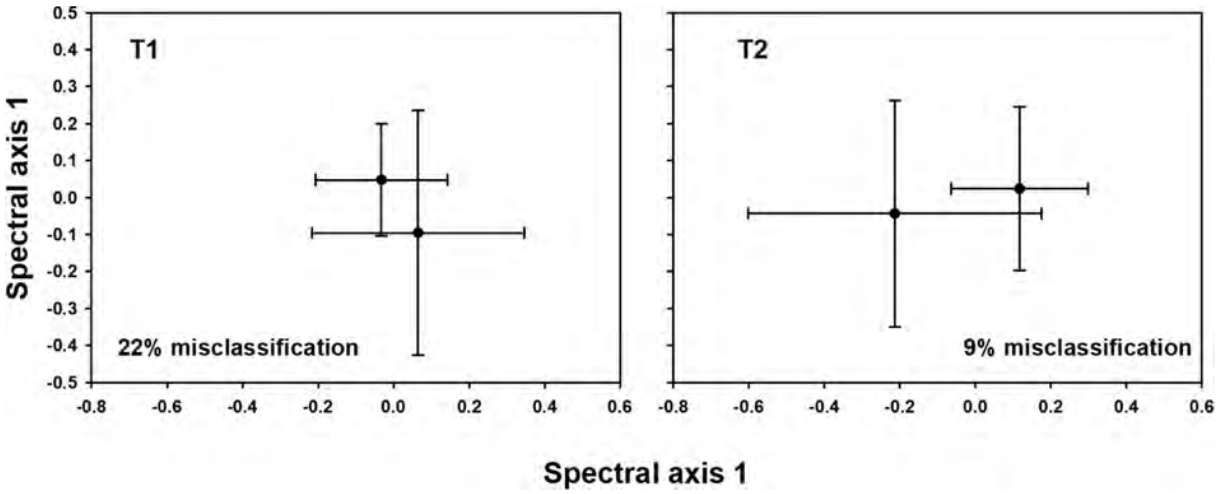


Figure 3. *Classification accuracies of black walnut inoculated vs. non-inoculated with G. morbida at 30- (T1) and 60-days (T2) post inoculation using foliar hyperspectral data.*

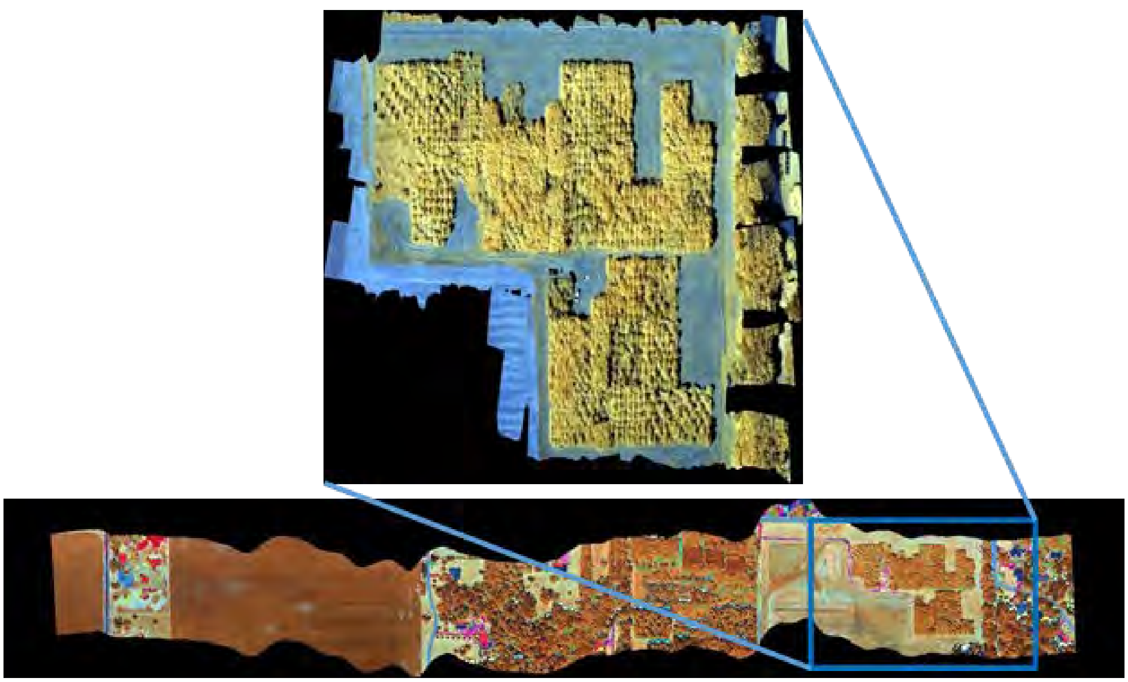


Figure 4. *False color images of full range hyperspectral data collected via unmanned aerial vehicle (top) manned aircraft (bottom) of research plots at Martell forest acquired in 2019.*

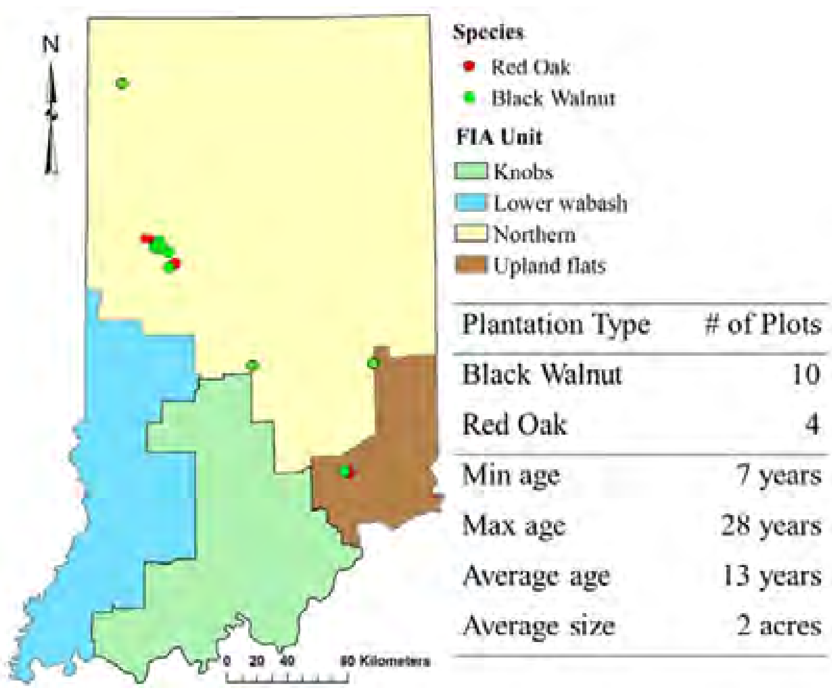
With input from the Executive Committee, a new project-based funding model was implemented for the HTIRC in 2018. Continued for a second year, funding was made available to support research projects that directly addressed our research priorities. All proposals were evaluated and selected by the HTIRC Executive Committee. We have committed more than $1 million over the next three years to support the projects listed below, and we again anticipate supporting additional projects this year. All future van Eck Scholars will be supported through this funding model. Beginning in 2020, we anticipate moving to fund new projects on a fiscal year that aligns with the Purdue fiscal year.

ECONOMIC ANALYSIS OF GROWTH & YIELD AND THINNING DECISIONS ON HARDWOOD PLANTATIONS

PRINCIPAL INVESTIGATORS

- **Mo Zhou**, *Assistant Professor, Department of Forestry and Natural Resources, Purdue University, (mozhou@purdue.edu)*
- **Lenny Farlee**, *Sustaining Hardwood Extension Specialist, Department of Forestry and Natural Resources, Purdue University*
- **Jingjing Liang**, *Assistant Professor, Department of Forestry and Natural Resources, Purdue University*
- **Elizabeth Jackson**, *HTIRC Engagement Specialist – Executive Director Indiana Forestry & Woodland Owners' Association – Executive Director Walnut Council, Department of Forestry and Natural Resources, Purdue University*
- **Yangyang Wang**, *Research Associate, Department of Forestry and Natural Resources, Purdue University*
- **Jim Warren,** *USDA Forest Service*

SUMMARY



Locations and summary statistics of HTIRC plots, to be used for calibrating the spatially explicit plantation growth and yield model.

In the Central Hardwood Region, the quantity and quality of hardwood timber critically depend on forest management decisions made by Nonindustrial Private Forest (NIPF) landowners, since they hold the largest share of woodland. NIPF plantations are in a unique and critical position to provide much-needed hardwood resources. However, there is a lack of research and tools enabling rigorous assessments of profitability of long-term investments in hardwood plantations. Partially due to this, the majority of these NIPF plantations remain unmanaged despite the existence of multiple public incentive programs providing financial and technical assistance to management. This proposed project aims at providing sound scientific evidence and tools to help promote forest management on hardwood plantations held by NIPF landowners. To this end, we propose to build the first spatially explicit plantation model for selected hardwood species and perform a series of analyses to determine the economic performance of various thinning decisions on hardwood plantations. Based upon these research outcomes, we will develop a suite of extension tools that allow users to 1) estimate growth & yield of individual trees in a user-defined mixed-species hardwood plantation; 2) simulate various thinning frequencies, intensities, and patterns; 3) estimate costs, returns, and investment profitability; 4) explore the potential economic benefits of joining public incentive programs. The deliverables of this project are expected to help motivate more NIPF landowners to actively manage hardwood plantations and increase enrollments in incentive programs. Furthermore, it will build a solid foundation for future assessments of other management strategies and techniques.

OBJECTIVES

This proposed project aims at **providing sound scientific evidence and tools to help promote forest management on hardwood plantations held by NIPF landowners.** To this end, our specific objectives are:

- Building the first spatially-explicit plantation growth & yield model for selected hardwood species;
- Quantifying the cost, return, and effectiveness of different thinning schedules and determining the optimal one with the highest profitability;
- Determining the effectiveness of different incentive programs to improve investment profitability;
- Developing a suite of extension tools based on Excel® to allow landowners and other stakeholders to perform the same analysis based on user-defined conditions.

ANTICIPATED OUTCOMES

Expected results comprise scientific research of growth & yield and thinning decisions on hardwood plantations, as well as extension tools that allow in-depth analysis by stakeholders. Furthermore, it will build a solid foundation to facilitate future assessments of other management strategies and techniques for mixed-species plantations that require spatially explicit information at the individual tree level. Expected impacts include improved decision-making and management of hardwood plantations, leading to greater productivity and value accrued to landowners, and more quality products available to industry. In addition, the inclusion of USDA cost-sharing programs in the analysis may raise awareness of these programs, resulting in increased enrollment and improved economic results for participants.

DEVELOPMENT OF MICROPROPAGATION AND REGENERATION SYSTEM FOR BLACK WALNUT

PRINCIPAL INVESTIGATORS

- **Rucha Karve**, *Post-Doctoral Research Associate, Department of Forestry and Natural Resources, Purdue University, (rkarve@purdue.edu)*
- **Richard Meilan**, *Professor, Department of Forestry and Natural Resources, Purdue University*

SUMMARY

Black walnut is one of the important hardwood trees for Indiana timber industry. Black walnut trees are both economically and ecologically significant. Propagation of black walnut has always been challenging due to dormancy and difficulties with rooting cuttings. To overcome long dormancy and problems with propagation by cuttings, the current propagation method heavily depends on a labor-intensive and time-consuming ritual of grafting. This limits fast generation of trees for silviculture, allows interference from heterologous rootstocks and delays selections for disease resistance in breeding program. Hence, there is a need to generate a robust and reliable micropropagation system to overcome these issues. Funding from HTIRC will be used to establish a micropropagation system

Juvenile stems will be collected from seedlings, similar to the one shown above.

for black walnut. Upon completion of this proposed work we will be able to prove that we have generated a successful micropropagation system that will be used as a platform to generate a transformation system to improve genetic resources for black walnut research. Our research is consistent with the mission of HTIRC which aims to "develop a clonal propagation system for black walnut".

Micro-shoots growing on solid media in vitro.

OBJECTIVES

We have three objectives in this proposal: 1) establish sterile cultures of selected cultivars of black walnut, 2) shoot multiplication and growth of healthy shoots, 3) rooting and establishing plants in vitro, and 4) successful transfer to soil and acclimation to ex-vitro conditions, including establishment in greenhouse.

ANTICIPATED OUTCOMES

The goal of the proposed research is to establish a micropropagation and regeneration system for black walnut. Our work will establish a platform for manipulating black walnut that will have a broader impact on hardwood tree improvement. Establishing a clonal propagation system will expedite tree improvement by providing many benefits. The same genotype (plant) can be tested in multiple soil, water and competition contexts to observe and measure the specific effects of soil, management, companion species, weeds and invasive plants, deer, pests and diseases, fertilizer, temperatures, without the confounding problem of half-sib relatives or rootstock effects. Clonal propagation provides uniformity with multiple ramets of the same trees for experimentation, common rootstocks for adaptation studies across wide range of environments, ecological studies as well as aid in the faster screening for disease resistance/responses with a uniform background without interference caused by grafting on different root stocks. Our research directly addresses the strategic plan of HTIRC that describes clonal propagation system of black walnut. Once we establish a protocol for black walnut and streamline it for efficient clonal propagation, we plan to submit future proposals to establish clonal propagation protocols for oaks and butternut.

PRECISE QUANTIFICATION OF FOREST DISTURBANCES WITH UAS (IDIF)

PRINCIPAL INVESTIGATORS

- **Joseph Hupy**, *Associate Professor, School of Aviation and Transportation Technology, Purdue University, (jhupy@purdue.edu)*
- **Songlin Fei**, *Professor, Department of Forestry and Natural Resources, Purdue University*

SUMMARY

Precision forest management requires detailed forest inventory information at the individual tree level. Field-based forest inventories are time consuming and labor intensive, and can be implemented only at limited spatial scales and temporal intervals. Delineation of individual deciduous hardwood trees with aerial remote sensing has long been sought for accurate forest inventory in hardwood forests. Taking advantage of recent advancements in two types of aerial remote sensing, LiDAR and UAS photogrammetry, the goal of this project is to *develop algorithms and automated tools that can be used by researchers and natural resources professionals alike to rapidly, efficiently, and cheaply inventory trees remotely for a large spatial area.*

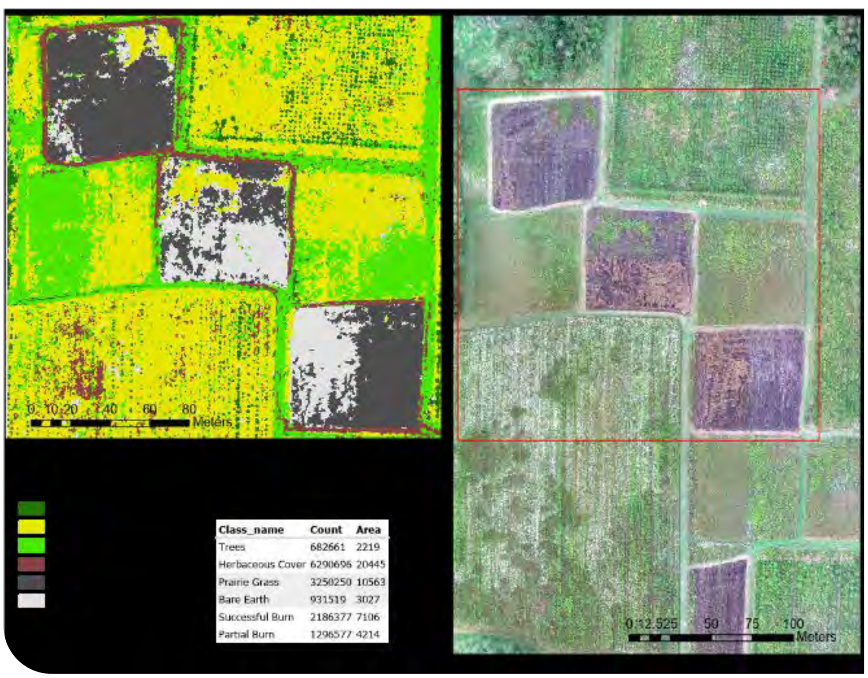
OBJECTIVES

The main goal of the questions presented in this proposal is to address how UAS can be properly utilized as an inventory mechanism prior to and after planned disturbance events such as controlled burns and timber harvests. Furthermore, we wish to address how UAS can then be used to monitor, map, and survey subsequent forest growth patterns in these disturbed areas at a range of temporal scales. Three main objectives can be delineated out of this main approach:

- Develop standardized data collection methods with UAS platforms prior to and after planned disturbance events such as timber harvest and controlled burns. This data collection will occur over several timber stands over a 3-year period, resulting in a robust data set for further analysis.
- Develop feature-based classification methods using UAS imagery for rapid and accurate classification of fire disturbance, vegetation cover, and harvest treatment intensities. Classification and quantification of results will be verified through ground truthing.
- Work directly with forest professionals, managers, and other stakeholders to best gather and disseminate data sets that reflect a wide diversity of planned disturbances over an equally diverse type of forest stands.

ANTICIPATED OUTCOMES

Innovative Data Collection and Analysis: By harnessing new developments in UAS technology that allow for gathering high-resolution imagery with centimeter accuracy using PPK technology, we can apply feature-based classification methods that were not before possible using traditional coarse resolution remotely sensed imagery. Land Use/Cover classification methods are nothing new, and go back to the very beginnings of GIS/Remote Sensing, but new here is the ability to build a framework that will effectively develop digital inventory records in a low-cost and accurate manner to classify features at the individual level at resolutions of several square centimeters. And because the imagery can be gathered less than an hour before the planned disturbance, you have some amazing potential for forestland management.



Relationships to and among other iDiF (integrated digital forestry) cluster proposals: The questions posed here complement and integrate with questions posed within the larger scope of the collaborative body of research presented by the iDiF initiative in both ongoing projects, and with 2019 proposed research topics. The research team assembled here not only consists of a diverse body of expertise, but also has members who overlap with other ongoing HTIRC proposals that are part of the iDiF. For example, we will use UAS-based tree delineation algorithms developed from an ongoing iDiF project for tree-level inventory in this proposed project for connections to other iDiF projects. The overarching goal of the iDiF initiative proposals are to develop and test a set of digital tools to assist HTIRC, and forestry in general, in modernizing forest improvement, management, and protection practices. This proposal takes that concept a step further by focusing on a specific set of applications in forest management where a digital tool, in this case UAS, can be used to effectively address several HTIRC strategic objectives in the context of planned disturbance events.

USING REMOTE SENSING TO CHARACTERIZE STRESS EPIDEMIOLOGY IN HARDWOOD FOREST STANDS (IDIF)

PRINCIPAL INVESTIGATORS

- **John Couture, Assistant Professor**, *Entomology, Purdue University, (couture@purdue.edu)*
- **Douglass F. Jacobs**, *Fred M. van Eck Professor of Forest Biology, Department of Forestry and Natural Resources, Purdue University*
- **Brady Hardiman**, *Assistant Professor, Department of Forestry and Natural Resources, Purdue University*
- *Matt Ginzel, Professor, Entomology, Purdue University*
- **Philip Townsend**, *Professor, Department of Forestry and Wildlife Ecology, University of Wisconsin-Madison*
- **Melba Crawford**, *Professor, Agronomy, Civil Engineering, and Electrical & Computer Engineering, Purdue University*

SUMMARY

Managed forests have considerable global economic and societal value. Globalization of trade over the past century has threatened this value due an increase in the introduction of non-native pest insects and pathogens into North America. At the same time, environmental change has also threatened forests, both directly, through negative impacts on tree health, and indirectly, by facilitating the spread of pest insects and pathogens. Remote sensing (RS) approaches offer advantages over traditional methods of forest management, specifically by increasing the scope and scale of information collected related with tree health. While recent advances in optical sensors have improved detection and quantification of tree health, there has been a lack of incorporating these approaches into monitoring at the spatial scale necessary to make informed management decisions To address this need, this project will integrate different forms of remotely-sensed data, collected over multiple time points and measurement scales, at two experimental forestry field stations with established forest stands that have known biotic and abiotic stressors present at various levels. We will use different machine learning frameworks to classify tree health to better understand the ability of remote sensing to inform forest health management decisions at stand levels. As a proof of concept, this project will focus on tracking pest insect and pathogen incidence and severity as well as the development of drought symptoms in both mixed and monoculture plantings within and across years. This project will be one of the first to explore the ability of remote sensing and advanced classification methodologies to track abiotic and biotic stressors in high-value hardwood tree species, both pre-visually and post-occurrence of visible symptoms, within a forest stand across both space and time.

OBJECTIVES

The main objective of this proposal is to integrate multi-spatial and temporal scale RS products with forest management scenarios. Specifically, we will focus on three areas of forest management: 1) tracking insect pest and pathogen incidence, severity, and spread, 2) early detection of drought stress-related symptoms, and 3) optimize RS acquisitions to determine the number of collections appropriate to make an informed management decision. We will integrate different forms of RS data, collected over multiple time points and measurement scales, at two experimental forestry field stations with plantations that have known biotic and abiotic stressors present at various levels. We will combine the RS data with high-resolution chemical and physiological data, and incorporate these data into different machine learning frameworks to better understand the utility of RS in forest health management. This project will be one of the first to explore relationships among genotypes, phenotypes, and RS data within a forest management framework, advancing our understanding of the ability of remote approaches to monitor forest health.

Using experimentally manipulated field sites, as opposed to natural systems, will allow us to not only impose stress through silvicultural treatments, but also collect more accurate reference information based on a more complete understanding of the history of various stressors present. The sites selected will provide range of stressors, including biotic (e.g., insect pests and pathogens) and abiotic (e.g., drought), and thus provide a range of test cases and use scenarios for determining generalizations and specificity among algorithms.

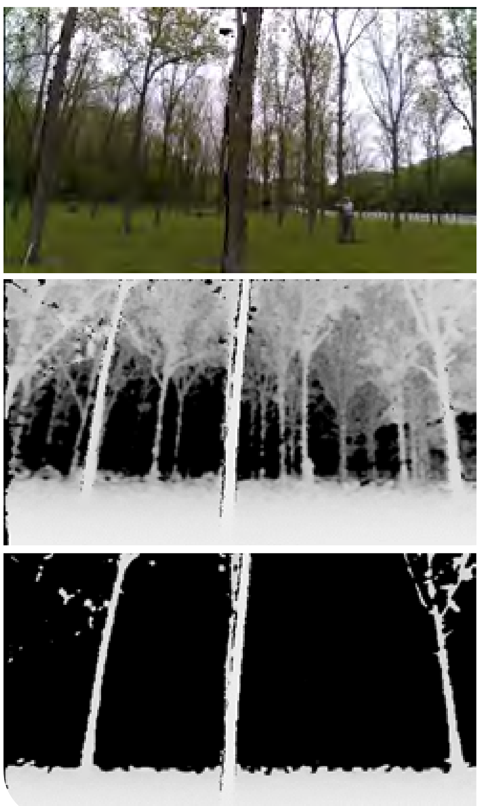
ANTICIPATED OUTCOMES

Outcomes from this project will be the most advanced and extensive effort to date to integrate multi-modal RS products into precision forest management. This project will generate outcomes that can directly inform potential management decisions involving timber harvest. The project team assembled has expertise in multiple areas that are related with forest science: genetics, chemistry and physiology, forest health, ecology, and monitoring using remote sensing. Importantly, this project builds on and leverages the current HTIRC-funded project for PIs Couture and Jacobs, which focuses on the use and scaling of hyperspectral information to detect stress, by incorporating outcomes generated from that research project to inform data collected in a multi-temporal and modal RS framework to assess interactions with other silvicultural treatments and improve forest health and productivity.

A NEW, FASTER, CHEAPER, AND EASIER WAY TO MEASURE HTIRC PLANTATIONS (IDIF)

PRINCIPAL INVESTIGATORS

- **Guofan Shao**, *Professor, Department of Forestry and Natural Resources, Purdue University, (shao@purdu.edu)*
- **Keith Woeste**, *USDA Forest Service Interim Project Leader, Molecular Geneticist*
- **Yung-Hsiang Lu**, *Professor, School of Electrical and Computer Engineering, Purdue University*



Color aligned (top), raw point cloud (middle), and cutoff point cloud (bottom) images obtained with TSP algorithm for a walnut plantation in Martell Forest owned by Purdue University in West Lafayette, IN. The spatial resolution of the nearest tree is 0.1 mm. Trees not actively measured are intentionally (and automatically) excluded (bottom).

SUMMARY

HTIRC needs to acquire data from its many (over 200) plantations. The time required to accurately measure and evaluate each individual tree is considerable, so relatively few plantations are measured each year. Furthermore, valuable information about tree form and quality is rarely obtained in part because current rating systems are highly subjective and may be unreliable. Recent advances in image matching algorithms and computation technology have made Structure from Motion (SfM) photogrammetry an attractive solution to the need for accurate, low-cost measurement and assessment of individual trees. We have spent nearly two years developing an algorithm for terrestrial stereoscopic photogrammetry through an integration of SfM photogrammetry principles and images acquired with stereo cameras. We have shown through a series of experiments that this new algorithm increased the speed and accuracy of tree diameter at breast height (DBH) measurements for black walnut plantations in Martell Forest. We will incorporate this algorithm and relevant hardware into an operational Low-cost Optical Gauging System (LOGS). With such a digital system, HTIRC breeders will be able to automatically measure tree diameters at different heights along the stem for every tree in HTIRC plantations, and update the HTIRC database in a timely manner. With the resolution of a few technical issues, this research goal is feasible now.

OBJECTIVES

The long-term goal of this project is to develop a Low-cost Optical Gauging System (LOGS) for efficient forest inventory and data management. LOGS will allow HTIRC scientists to obtain accurate, up-to-date data on all the trees in their breeding program. LOGS will be used to identify individual trees, estimate tree diameters at different heights along the stem, calculate log volumes, map tree locations, produce a 3-D image of each stem in a plantation, and transfer the data to the existing HTIRC database. The system will not require special expertise to operate. Improving on the algorithm we developed so far (Eliopoulos et al. 2019), this proposed research has three objectives:

- To develop and demonstrate a portable device capable of real-time tree measurements of tree diameters at regular height intervals. Although the data processing of terrestrial stereoscopic photogrammetry is much faster than for the popular SfM photogrammetry (Figure 2), it cannot yet provide "real time" output, which we consider essential.
- To develop an algorithm to automatically locate (in a GIS framework) individual trees to avoid redundant tree measurements or skipped measurements on the ground. This functionality will also be helpful to take multiple measurements and obtain mean values for each tree, improving the accuracy of tree measurements.
- To demonstrate the integrated system with a broad range of HTIRC plantations and selected natural forest stands in Indiana. The system will be evaluated for use in a range of tree species and forest types.

ANTICIPATED OUTCOMES

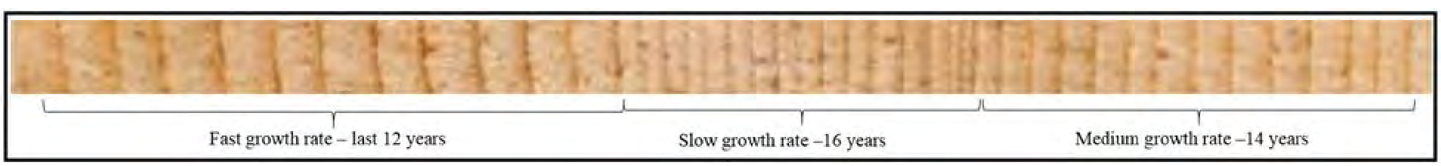
This proposal directly addresses HTIRC Organizational Objective 4: Develop digital forestry technologies. Tools developed in this proposed project can greatly enhance our ability to address HTIRC Strategic Direction 1: Produce hardwood trees with desirable traits, using both classical tree breeding and novel tree improvement techniques, and 2: Improve management strategies and techniques to enhance the ecological sustainability and economic benefits of hardwood forests.

We propose to develop the technology described above over the course of three years. By the end of 2020, we will demonstrate that LOGS can acquire images from HTIRC plantations, determine diameters of every tree in a plantation at multiple heights (taper), and produce an image database. By the end of 2021, we will develop methods to automatically mark tree locations for GIS analysis and store all relevant data for each tree in a form retrievable through the existing HTIRC database. By the end of 2022, we will report on how to apply LOGS for its operational uses in both planted and naturally-regenerated forests.

GEO-REFERENCED AND IMAGED-ASSISTED IN-SITU BIOMETRIC EVALUATION TOOL FOR PRECISION GROWTH AND YIELD MODELING (IDIF)

PRINCIPAL INVESTIGATORS

- **Rado Gazo, Professor**, *Department of Forestry and Natural Resources, Purdue University, (gazo@purdue.edu)*
- **Bedrich Benes**, *George W. McNelly Professor of Technology, Department of Computer Graphics Technology, Purdue University*
- **Songlin Fei**, *Professor, Department of Forestry and Natural Resources, Purdue University*



SUMMARY

This proposal for development of a geo-referenced and image-assisted biometric evaluation tool for precision tree growth and yield modeling is a part of the integrated Digital Forestry (iDiF) effort. Deliverables include the developed and pilot-tested tool in the first year, and software for analysis and geo referenced database in years 2 and 3.

In addition to meeting HTIRC strategic objective and providing immediate, year 1 deliverable to industry and research stakeholders, funding this proposal will also accomplish two other things. One, it will help to align and integrate Dr. Gazo's research program with goals of HTIRC; and two, upon successful conclusion, it will provide data, prove the concept, and serve as a justification for development of the mobile CT scanner for standing trees, the ultimate solution to many questions that biometricians, forest managers, tree breeders, researchers and others are asking.

OBJECTIVES

The ultimate objective of this project is to quantify the change in the growth rate of a tree, and to link it to the previous stand management practices, site index, soil type, local weather patterns, climate change and other known factors, in real time and place. The following three specific objectives will help us get there: 1) develop appropriate image acquisition hardware and pilot-test it on the TigerCat™ log bucking equipment; 2) develop software for image analysis and biometric data collection; 3) relate tree biometric information to geo location of origin.

ANTICIPATED OUTCOMES

For objective #1: Specifications for image acquisition hardware setup that will be capable of acquiring acceptable images. At least one working system will be constructed.

For objective #2: Ready-to-use software for image processing, analysis and archiving. Software will be capable of extracting biometric features such as minimum, maximum and average diameter inside bark, growth ring count, growth rate, and hardwood and sapwood proportion.

For objective #3: Geo-referenced database of collected sample images from experiment trees.

Additionally, we will attempt to develop an image acquisition system that will potentially use a camera of a GPS-enabled smartphone or tablet and an app to store, process and archive images acquired by researchers in the field. This deliverable is based on availability of time and funds in Year 3 of the project.

IMPROVEMENT ACTIVITIES

Operational improvement aims to develop improved planting stock for the Central Hardwood Forest Region of the U.S. We utilize classical breeding to select parents, test progeny, and evaluate growth rate and timber quality and to develop disease resistance in two native endangered species as well as new and emerging forest pests. Our germplasm and plant material are a valuable resource for our HTIRC colleagues who conduct wide-ranging basic research from forest health and ecology to genomics and silviculture.

Over nearly two decades, our operational improvement program has been collecting and evaluating elite timber germplasm of black walnut, black cherry, and northern red oak. For each species, we have collected 120 to 700 accessions from the wild or previous plantings that exhibit above average growth and timber quality. American chestnut and butternut breeding mainly consists of screening each species to its exotic disease and then selecting the most resistant parents and progeny to develop new breeding orchards.

A novel feature of our program is the fact that our progeny test seed comes from clone banks and breeding orchards. Because these species are difficult to artificially pollinate (except for chestnut), our principle breeding technique is to create isolated orchards to naturally inter-mate and collect open pollinated seed. For each parent tree, we progeny test its family at six different sites over a minimum of two years.

Our progeny testing design has been primarily 8-foot x 8-foot grid spacing (680 tree/acre) with two progeny per family per block, in an "incomplete" manner. Progeny tests range from 12 to 36 blocks (each block has 48 trees) depending on the availability of seedlings and land. Thus, in every block, we have 24 families represented each with two trees. The incomplete block design spreads out progeny across the site to minimize soil variation effects and improve the evaluation of the genotypes. So, if we have 20 blocks in a given test, families with 24 or 20 seedlings will occur in just 12 or 10 blocks, not every block, initially as two seedlings per family.
Other important cultural features for our successful progeny testing are deer exclusion and weed control for the first three years. Finally, we minimally prune trees but achieve a single-stem status for all trees after three- and five-year data is collected.

We measure heights at 3, 5, 8, 10, 13, and 15 years, and include DBH and a subjective timber quality rating at five years and add in merchantable log length at 10 to 15 years. We achieve high stocking rates in all our plots with naturally high-survival, or we add “filler” trees at three years to achieve 95% or better stocking. By year eight, we no longer need deer or weed control. Once tenth-year data is collected and crown canopies are closed, we thin out half of the trees. Some tests were designed for row-thinning (paired progeny planted side-by-side) and others are selectively thinned down 50%; the poorer tree of each family pair is removed. This system has worked out very well to keep all trees and families free-to-grow until final measurements at 15 years.

Once a family has been tested completely at six sites and over at least two years, we conclude on the breeding performance of that parent (mother tree). Timber performance cannot be reliably evaluated until the trees are at least eight years old, and 10, 13, and 15-year data further validate genetic performance. In some cases, particularly northern red oak, we have added a feature of planting progeny much wider apart and utilizing trainer rows that are thinned after 10 years to develop long-term, second-generation, seedling-improved northern red oak orchards. In disease resistance breeding of chestnut and butternut, resistant parents and progeny are identified after screening 5 years for chestnut and 10 years for butternut; resistant selections are propagated into new 2nd generation seed/breeding orchards at new disease-free sites.

2019 was a good year for Operational Tree Improvement at the HTIRC, thanks to our new Research Forester (Caleb Kell) and we have caught up on a lot of backlogged work. We will have much more to report in 2020.

Melanie Moore (USDA Forest Service) evaluating butternut canker disease in our 2nd screening block at Purdue.

MEASUREMENTS: We measured all three of our oldest (2009) black cherry progeny tests as well as two from 2010. In addition, we measured four walnut progeny tests, three from 2009 and one from 2008 at SEPAC. Finally, we measured two new butternut screening plots planted in 2008 and 2009 with progeny from both our clone bank/breeding orchard at Purdue and our colleagues' (Melanie Moore and Mike Ostry, USDA Forest Service, Rosemont, Minnesota) grafted orchard. All trees had been inoculated in 2011-12 and now are under a natural butternut canker epidemic. The results showed most of the resistance occurs in hybrids, but at this time we still have a number of healthy pure butternuts.

MANAGEMENT: Last year was a difficult one as the spring was the wettest in HTIRC history. The Illinois Walnut Council had a winter field day and thinned our 2010 Forest Glen butternut, hybrid butternut, walnut and red oak trees, one of seven such plots we planted in 2010-2011. That help was appreciated along with the Purdue FNR Martell Forest Crew who provided additional vehicles and help during that time. In February, we assisted Lee Eckart (Danzer Forestland) with the final thinning of seedling trainer trees in our select cherry, white oak, and walnut seed orchard. The grafted white oaks were suffering because many were severely shaded from their more vigorous seedling trainers the last few years. We collected scion wood from every healthy surviving select white oak clone to add into our breeding orchards at Purdue. We also thinned several black cherry and walnut test plots at Purdue and SEPAC, as well as a third northern red oak progeny test/seed orchard plot. In spring 2019, we provided our HTIRC squirrel-proof walnut seed planting system to HTIRC researchers who planted seed for cutting-edge microbiome research in Indiana and Washington State. We also assisted a new deer impact study to optimize small deer-fence construction.

Elite white oak grafted clones after thinning in July of 2019 in our Danzer Forestland orchard.

Planting the butternut screen at Bell Center, WI in May 2019.

NEW PLANTINGS: We planted our largest butternut screening test plot with the USDA Forest Service and the WI-DNR Tree Improvement at Bell Center, Wisconsin, in May. In one day, we planted just over 3,000 butternut from 37 families (4 hybrid families for the first time in Wisconsin). To achieve this, we pre-sorted all the trees at Martell over three days in February with help from the Forest Service Oconto River Seed Orchard in northern Wisconsin. The plot was designed by Dr. Paul Berrang, (USDA Forest Service, Region 9 Geneticist) based on our first two HTIRC butternut canker disease screening blocks at Martell Forest that utilize inoculations to start the disease and then rely on natural spread.

Grafted American chestnuts from our 2018 American Chestnut Foundation (TACF) grant with Nick LaBonte, Aziz Ebrahimi, and Jarred Westbrook were planted in the Duke American Orchard at Martell Forest in May. We painted these with a flat interior white latex paint with a fungicide to protect them from blight. These trees all survived and will provide a source of new American chestnut diversity for future breeding.

Given the success of our 2015 Forest Service State & Private-Forest Health Grant to test a new and very practical method of screening butternut for resistance to butternut canker disease, we added an additional 100 seedlings from more than a dozen new families not previously screened (pure and hybrid) into our oldest screening block at Martell. The first batch of such seedlings, planted in 2015 that we reported on in 2018, are separating out very well into highly and moderately resistant categories, with the moderate to highly susceptible dying by six years.

SELECTIONS: We made numerous new butternut and hybrid butternut selections last year. We evaluated progeny from 2008 and 2009 in our second butternut canker screening block. The results reflected those from our first screening block (2003 and 2004 progeny) and also were very similar to our new and improved screening method we reported last year—planting seedlings in the existing middle-rows after 90% or more thinning. New selections can be made from our 2015 seedlings starting next winter.

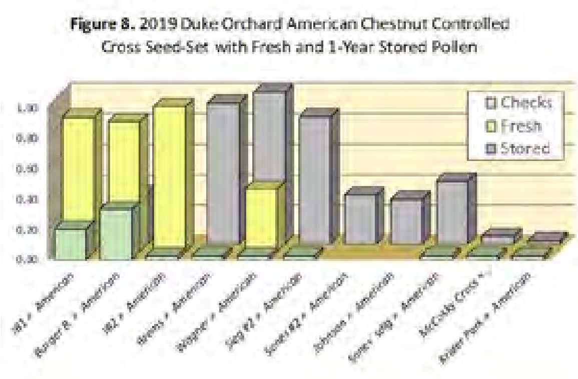
GRAFTING: We added new elite white oak clones selected by Lee Eckart (Danzer Forestland) into our precocious and elite white oak breeding orchards at the Martell Forest and Richard G. Lugar Farm last May. We are glad to report that we have at least one strong successful graft from each clone. These 17 clones nearly double our elite selections from across Indiana.

A new white oak field graft starting to grow in June 2019.

We grafted a new elite black cherry orchard for our Rush County, Indiana, HTIRC research site in 2019. In August 2018, 15 clones were selected for a new trait, high-percentage of live crown, a datum employed by Matt Ginzel's lab and others in forest/tree health research.

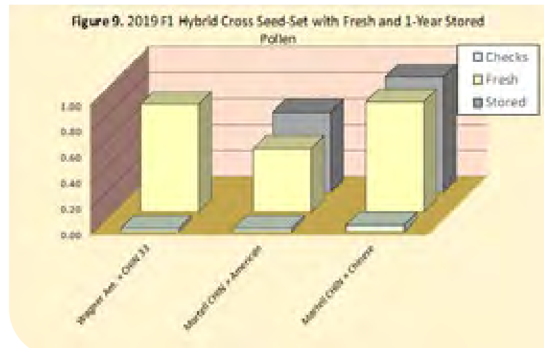
Ten walnut clones under study with Ginzel's lab and cooperators at the University of Tennessee, Knoxville, and Walla Walla, Washington, were grafted to be planted at the University of Tennessee in 2020.

The new grafted elite black walnut seed orchard we field grafted in Rush County in 2018 was staked with 10-foot poles and pruned as orchard trees in June 2019. The tremendous growth of the successful grafts is a result of our efforts and that of our cooperator, Mike Forgey. This orchard is off to a great start and will provide seed to further our breeding efforts in fall 2021, and has potential to become a new and important source of improved black walnut timber seed in the short term.



CROSS POLLINATION & POLLEN STORAGE: In 2018, we harvested extra American and Chinese chestnut pollen for the first time at the HTIRC. Frozen pollen, stored for at least one full year, makes breeding much more efficient since we can have all desired pollen available at the start and throughout the female bloom. Figure 8 shows the results of fresh and stored pollen on the successful controlled cross pollination of various American chestnut clones and genotypes. The checks are seeds set in shoots that were bagged and not pollinated. The female trees 'IB1' and 'Burger B.', were bagged too late to exclude pollination in the orchard. For the other nine mother trees, we had zero pollen contamination. There is no significant difference between fresh and stored pollen to effectively set American chestnut seeds, and we will utilize this method in the future to store and freeze pollen.

Since 2015, we have been working on a new breeding plan with the American Chestnut Foundation (TACF) and the IN-TACF to improve chestnut blight resistance in hybrid chestnut. Our first step has been to produce upwards of 15 new F1 lines. We created two more lines last year with stored and fresh pollen of both American and Chinese chestnut, and the results of our seed set through crossing for these is listed in Figure 9, along with a Chinese x Chinese cross. We have found that these interspecific crosses (two species) are not as effective at seed set as crosses among different trees of the same species. This study was our first direct comparison on the same "Martell CHIN" Chinese tree that is isolated in the Xi Sigma Pi Arboretum at Martell and has proven to be a very good tree for such studies, training, and education.



SEED HARVEST / STORAGE: Black cherry seed production was excellent in the summer of 2019. We harvested over 200,000 seeds in total from our two oldest breeding orchards (2005-06) and main clone bank (2007), all three of which contain about 60% NW Pennsylvania selections and about 40% from Indiana and Michigan (85 clones in total among these). In addition, we had our first large seed crop from an isolated small breeding orchard composed of just Michigan and Indiana clones (2005). We assisted the Jacobs group obtain black cherry seed in January 2019 for a new project by germinating cherry seed we had stored in a freezer at –20 C° since 2012 and found very good germination after about 70 days of stratification in sand. With that preliminary positive result, we made the decision to store excess seed from these four important breeding plots and now have an excellent supply of improved black cherry on-hand to support future breeding, seed physiology, and ecology studies at the HTIRC.

Harvesting black cherry from our Michigan and Indiana only grafted seed orchard at the Richard G. Lugar Farm at Purdue.

In support of the Jacobs, Meilan, and Ginzel Labs, we collected black walnut from new regions of the native black walnut range – Maryland and Kansas. Both targeted areas of those states are at the same latitude as Indianapolis and represent the most eastern and western edges of the native range. We also harvested HTIRC Indiana walnut seed from our non-select and select/improved clones, with excellent help from the Martell Crew. Stratified seed in the spring of 2020 will be utilized to support drought/water stress research and TCD epidemiology/ microbiome work. A subset of improved clones from our most important breeding orchard were harvested for a new tissue culture clonal propagation project to begin this year, led by Rucha Karve and Rick Meilan.

The role of HTIRC outreach is to connect our partners, collaborators, and stakeholders with the people, information, and products of the HTIRC. We also engage a broad audience to explain the benefits of forest research, management, and tree improvement for people and the environment.

Jim McKenna discussing American chestnut improvement techniques.

The following are utilized in our outreach/engagement efforts:

HTIRC NEWS

The HTIRC website and semi-annual email newsletter are two of the methods used to connect with our partners, collaborators, and stakeholders. The HTIRC website (https://htirc.org) contains an updated list of publications reflecting research papers and landowner/land manager resources, as well as events involving HTIRC staff. Thirty-six research papers were added to the website in 2019, making that information broadly available to our audiences.

We produced one email newsletter in fall 2019 due to the publication of our first annual newsletter at about the time our spring newsletter is normally released. Newsletters are distributed to subscribers and posted on our website. The Fall/Winter 2019 newsletter included 10 articles highlighting recent research projects, publications, events, awards and recognition. We will move to a summer and winter issue newsletter schedule for 2020 to complement the spring release of the annual report. Subscribe to the email newsletter or access past issues at https://htirc.org/resources/newsletters/

STAKEHOLDER ENGAGEMENT

We engage with partners, collaborators, and stakeholders through consultation, service on boards and committees, education events and field days, information sharing, and collaboration on projects. We also extend the reach to work with landowners and resource managers through education events and products.

Members of the HTIRC staff serve on boards or assist with education programs for organizations including:

- The Walnut Council
- Tree Farm
- Indiana Hardwood Lumbermen's Association
- The American Chestnut Foundation
- Society of American Foresters
- Indiana Forestry and Woodland Owners Association

Some of the educational programs provided annually by Lenny Farlee, serving as an Extension Forester with the HTIRC and Purdue University Department of Forestry and Natural Resources, include:

- Landowners Conservation Tree Planting Workshops
- Forest Management for the Private Woodland Owner course
- Natural Resources Conservation Service/Conservation Partnership Tree Planting Training
- Tree Farm Landowners Field Days
- Forest Pesticide Applicators Continuing Education Program
- Walnut Council Field Days

Lenny Farlee discussing invasive brush removal techniques at a landowner workshop.

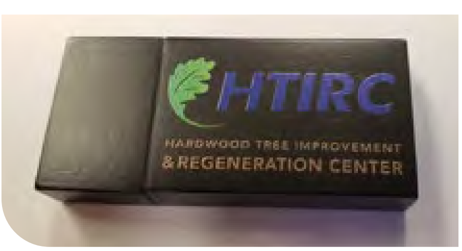
Liz Jackson, Engagement Specialist with the HTIRC, in addition to other roles at Purdue University Department of Forestry and Natural Resources, provides extension articles, presentations and field days/workshops. She works with partner organizations with an interest in application of HTIRC research, including the 725-member Walnut Council, through newsletter articles and conference presentations, sharing the latest management techniques with foresters and landowners.

NEW EXTENSION PRODUCTS

We provided lab and field tours and programs for the Natural Resources Teacher Institute, which provides classroom and non-traditional educators' exposure to forest management, science and industry through a week-long emersion experience. Eighteen teachers visited with HTIRC researchers and staff in labs and our field sites to learn about tree genetics, soils, tree improvement, and practices like grafting and plantation management.

We cooperated with the Walnut Council to create a flash drive archive of Walnut Council symposium proceedings, newsletters, and black walnut management publications. This archive will provide a valuable library of black walnut management information covering the 50-year history of the Walnut Council.

The Planting and Care of Fine Hardwood Seedlings series provides practical information to landowners and managers for the establishment and management of hardwood trees in plantations and native forests. These publications are utilized by landowners and resource managers extensively, with over **40,600** publication downloads/views in 2019.



Association of Consulting Foresters flashdrive

We had the opportunity to provide our publications to a national convention of the Association of Consulting Foresters in the summer of 2019. We provided a flash drive loaded with our publications and additional information on planting and managing hardwood trees to over 150 professional foresters attending this event. The consulting foresters are one of the primary contact points for professional forestry advice and assistance to landowners.

We are also cooperating with the Indiana Division of Forestry and Purdue Extension to produce a series of landowner-oriented videos, “Woodland Stewardship for Landowners,” on topics like pruning hardwood trees, identifying and controlling invasive plant species, safe handling and use of herbicides, accessing cost sharing programs, and several forest management practices and techniques. Several of these publications will be completed and posted in 2020.

PhD candidate Andrea Brennan produced a podcast on the plight of butternut trees based on research she and other investigators have done. The podcast episode is located at www.indefenseofplants.com/podcast/2019/9/29/ep-232-the-plight-of-the-butternut

2018 HTIRC annual meeting field tour

ANNUAL ADVISORY COMMITTEE MEETING

In September, HTIRC hosted 17 members of the HTIRC advisory committee to update them on the latest HTIRC research and field work. Topics presented by research scientists and students included new work in digital forestry and ongoing efforts in invasive shrub control.

EDUCATION

Developing future researchers and practitioners with expertise in the science and application of tree improvement, management, and protection of hardwood forests continues to be a fundamental objective of the HTIRC. We currently support three PhD students and five MS students with van Eck funds. Four students graduated this year:

HTIRC STUDENTS WHO GRADUATED IN 2019

- **Lilian Ayala Jacobo** (MS – Jacobs) studied freeze tolerance and genetic variability of *Acacia koa*.
- **David Mann** (MS – Saunders) studied the effect of prescribed fire on timber quality.
- **Caleb Redick** (MS – Jacobs) studied quantifying impacts of deer browsing and mitigation efforts on hardwood forest regeneration. He is now employed as a Research Assistant by Purdue in the Department of Forestry and Natural Resources.
- **Franklin Wagner** (MS – Fei and Hardiman) studied forest structure using remote sensing techniques.

MOVING ON IN 2019

- **Anna Sugiyama** (postdoctoral researcher with Douglass F. Jacobs) investigated intraspecific variation in functional traits for forest restoration in *Acacia koa*. Anna has taken a position as an assistant professor of Botany at the University of Hawai'i at Mānoa.
- **Holly Wantuch** (postdoctoral researcher with Matt Ginzel) has taken a position as an entomologist/field office coordinator with the Oregon Department of Agriculture, Plant Protection & Conservation Programs, in Eugene.

CURRENT VAN ECK SCHOLARS

- **Andrea Brennan** (PhD – Jacobs) is evaluating the use of hybrid butternut trees as a potential restoration tool through disease screening, assessment of environmental tolerances, and evaluation of perceptions to the use of hybrid trees for restoration.
- **Minjee (Sylvia) Park** (PhD – Couture and Jacobs) is studying hyperspectral phenotyping of tree physiological responses to biotic and abiotic stresses.
- **Geoffrey Williams** (PhD – Ginzel) is characterizing community interactions that influence the severity of thousand cankers disease in eastern black walnut.
- **Molly Barrett** (MS – Saunders) is focused on regeneration response of oaks to prescribed fire and gap-based harvesting in the Central Hardwood Region (CHFR).
- **Sarah Cuprewich** (MS – Saunders) is quantifying various effects of prescribed fire on oak regeneration.
- **Madeline Montague** (MS – Jacobs) is focused on understanding below-ground interaction in mixed hardwood plantings that contain American chestnut.
- **Aishwarya Chandrasekaran** (MS – Shao) is interested in the field of remote sensing and image processing.
- **Zachary Miller** (MS – Hupy) is studying using unmanned aerial systems (UAS) for geospatial data collection in forestry and conservation efforts.
- **Zhaofei Wen** (postdoctoral researcher with SonglinFei) is interested in retrieving forest parameters (i.e., tree height, tree diameter, species composition, forest volume, etc.) at large scale, using remote sensing and GIS technologies.

2019 RESEARCH PUBLICATIONS

HTIRC-related research papers published in 2019 are listed below. To see a listing of research from previous years, please visit the HTIRC website "Resources" tab: https://htirc.org/research/research-publications/

Chen, A., Peng, S., and **Fei, S.** (2019). "Mapping global forest biomass and its changes over the first decade of the 21st century." Science China Earth Sciences **62**(3): 585-594.

Ebrahimi, A., Mathur, S., **Lawson, S.S.**, LaBonte, N.R., Lorch, A., **Coggeshall, M.V.**, and **Woeste, K.E.** (2019). "Microsatellite Borders and Micro-sequence Conservation in Juglans." Scientific Reports **9**: 3748.

Fahey, R.A., J.W., Gough, C.M., **Hardiman, B.S.**, Nave, L.E., Tallant, J.M., Nadehoffer, K.J., Vogel, C., Scheuermann, C.M., Stuart-Haentjens, E., Haber, L.T., Fotis, A.T., Ricart, R., and Curtis, P.S. (2019). "Defining a spectrum of integrative trait-based vegetation canopy structural types." Ecology Letters.

Gauthier, M.M., and **Jacobs, D.F.** (2019). "Photosynthewtic parameters of Juglans nigra trees are linked to cumulative water stress." Canadian Journal of Forest Research **49**(7): 752-758.

Gough, C.M., Atkins, J.W., Fahey, R.T., and **Hardiman, B.S.** (2019). "High rates of primary production in structurally complex forests." Ecology **100**(10): e02864.

Greenler, S.M., and **Saunders, M.R.** (2019). "Short-term spatial regeneration patterns following expanding group shelterwood harvests and prescribed fire in the Central Hardwood Region." Forest Ecology and Management **432**: 1053-1063.

Guo, O., **Fei, S.**, Potter, K.M., Liebhold, A.M., and Wen, J. (2019). "Tree diversity regulates forest pest invasion." Proceedings of the National Academy of Sciences of the United States of America 116(15): 7382-7386.

Jenkins, M.A., and Webster, C.R. (2019). "Age structure and recruitment of Trillium luteum (Trilliaceae) populations in secondary forests of the southern Appalachian Mountains." The Journal of the Torrey Botanical Society **146**(4): 239-251.

Jo, I., **Fei, S.**, Oswalt, C.M., Domke, G.M., and Phillips, R.P. (2019). "Shifts in dominant tree mycorrhizal associations in response to anthropogenic impacts." Ecology **5**(4): 1-8.

Knott, J.I.A., Desprez, J.M., Oswalt, C.M., and **Fei, S.** (2019). "Shifts in forest composition in the eastern United States." Forest Ecology and Managment **433**: 176-183.

LaRue, E.A., **Hardiman, B.S.**, Elliott, J.M., and **Fei, S.** (2019). "Structural diversity as a predictor of ecosystem function." Environmental Research Letters **14**(11).

Li, Z., Yang, J., Shang, B., Xu, Y., **Couture, J.J.**, Yuan, X., Kobayashi, K., and Feng, Z. (2019). "Water stress rather than N addition mitigates impacts of elevated O3 on foliar chemical profiles in poplar saplings." Science of The Total Environment **707**.

Liao, J., **Shao, G.**, Wang, C., Tang, L., Huang, Q.., and Qiu, Q (2019). "Urban sprawl scenario simulations based on cellular automata and ordered weighted averaging ecological constraints." Ecological Indicators **107**.

Löf, M., Madsen, P., Metslaid, M., Witzell, J., and **Jacobs, D.F.** (2019). "Restoring forests: regeneration and ecosystem function for the future." New Forests **50**(2): 139-151.

Maltoni, A.I., Mariotti, B., Tani, A., Martini, S., **Jacobs, D.F.**, and Tognetti, R. (2019). “Natural regeneration of Pinus pinaster facilitates Quercus ilex survival and growth under severe deer browsing pressure.” Forest Ecology and Management **432**: 356-364.

McCallen, E., Knott, E., Nunez-Mir, G.C., Taylor, B., Insu, J. and **Fei, S.** (2019). “Trends in ecology shifts in ecological research themes over the past four decades.” Frontiers in Ecology and the Environment **17**(2): 109-116.

Mechergui, T., Pardos, M., and **Jacobs, D.F.** (2019). “Influence of mulching and tree shelters on 4-year survival and growth of zeen oak (Quercus canariensis) seedlings.” Journal of Forestry Research **30**(1): 129-141.

Moore, M., Juzwik, J., Miller, F., Roberts, L., and **Ginzel, M.D.** (2019). “Detection of Geosmitia morbida on Numerous Insect Species in Four Eastern States.” Plant Health Progress **20**(3): 133-139.

Mushinski, R.M., Phillips, R.P., Payne, Z.C., Abney, R.B., Jo, I., **Fei, S.**, Pusede, S.E., White, J.R., Rusch, D.B., and Raff, J.D. (2019). “Microbioal mecanismas and ecosystem flux estimation for aerobic NOv emissions from deciduous forest soils.” Proceedings of the National Academy of Sciences of the United States of America **116**(6): 2138-2145.

Nunez-Mir, G. C., Guo, O., and **Fei, S.** (2019). “Predicting invasiveness of exotic woody species using a traits-based framework.” Ecology Ecological Society of America **100**(10): e02797.

Phillips, R.P., Brandt, L., Polly, P.D., Zollner, P., **Saunders, M.R.**, Clay, K., Iverson, L., and **Fei, S.** (2019). “An integrted assessment of the potential impacts of climate change on Indiana forests.” Climate Change: 1-15.

Reynolds, H.L., Brandt, L., Fischer, B.C., **Hardiman, B.S.**, Moxley, D.J., Sandweiss, E., Speer, J.H., and **Fei, S.** (2019). “Implications of climate change for managing urban green infrastructure: an Indiana, US case study.” Climate Change.

Shao, G., Shao, G., and **Fei, S.** (2019). “Delineation of individual deciduous trees in plantations with low-density LiDAR data.” International Journal of Remote Sensing **43**(1): 346-363.

Shao, G., Tang, L., and Liao, J. (2019). “Overselling overall map accuracy misinforms about research reliability.” Landscape Ecology **34**(11): 2487-2492.

Soto, D.P., Puettmann, K.J., Fuentes, C., and **Jacobs, D.F.** (2019). “Regeneration niches in Nothofagus-dominated old-growth forest after partial disturbance: Insights to overcome arrested succession.” Forest Ecology and Management **445**: 26-36.

Stackhouse, T., Oren, E., Boggess, S., **Ginzel, M.D.**, Hadziabdic, D., Trigiano R.,and Klingeman, W. (2019). “An enhanced strategy for molecular detection of thousand cankers disease.”

Stanis, S., Wiedenbeck, J., and **Saunders, M.R.** (2019). “Effect of Prescribed Fire on Timber Volume and Grade in the Hoosier National Forest.” Forest Science **65**(6): 714-724.

Sun, Y.W., Hou, N., **Woeste, K.**, Zhang, C., Yue, M., Yuan, X.Y., and Zhao, P. (2019). “Population genetic structure and adaptive differentiation of iron walnut Juglans regia subsp. sigillata in southwestern China.” Ecology and Evolution.

Thyroff, E., Burney, T., Mickelbart, M.V., and **Jacobs, D.F.** (2019). “Unraveling Shade Tolerance and Plasticity of Semi-Evergreen Oaks: Insights From Maritime Forest Live Oak Restoration.” Frontiers in Plant Science 10:1526.

Thyroff, E., Burney, O.T., and **Jacobs, D.F.** (2019). "Herbivory and Competing Vegetation Interact as Site Limiting Factors in Maritime Forest Restoration." Forests **10**: 950.

Williams, G.M. and **Ginzel, M.D.** (2019). "Spatial and Climatic Factors Influence Ambrosia Beetle (Coleoptera: Curculionidae) Abundance in Intensively Managed Plantations of Eastern Black Walnut." Environmental Entomology.

Yang, H., Zhang, X., Luo, H., Liu, B., Shiga, T.M., LIi, X., Kim, J.I., Rubinelli, P., Overton, J.C., Subramanyam, V., Cooper, B.R., Mo, H., Abu-Omar, M.M., Chapple, C., Donohoe, B.S., Makowski, L., Mosier, N.S., McCann, M.C., Carpita, N.C., and **Meilan, R.** (2019). "Overcoming cellulose recalcitrance in woody biomass for the lignin-first biorefinery." Biotechnology for Biofuels **12**: 171-188.

Yang, H., Benatti, M.R., Karve, R.A., Fox, A., **Meilan, R.**, Carpita, N.C., and McCann, M.C. (2019). "Rhamnogalacturonan-I is a determinant of cell–cell adhesion in poplar wood." Journal of Plant Biotechnology. https://doi.org/10.1111/pbi.13271

Zhang, B. W., Xu, L.L., Li, N., Yan, P.C., Jiang, X.H., **Woeste, K.E.**, Lin, K., Renner, S.S., Zhang, D.Y., and Bai, W.N. (2019). "Phylogenomics Reveals an Ancient Hybrid Origin of the Persian Walnut." Molecular Biology and Evolution **36**(11): 2451-2461.

NOTES

HTIRC™

HARDWOOD TREE IMPROVEMENT
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