HTIRC
HARDWOOD TREE IMPROVEMENT & REGENERATION CENTER

2021 ANNUAL REPORT

PURDUE UNIVERSITY | Forestry and Natural Resources

FOREST SERVICE U.S. DEPARTMENT OF AGRICULTURE

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.

Hardwood Tree Improvement Center
Purdue University

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West Lafayette, IN 47907-2061

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Cover photo: *American chestnut seedlings in a greenhouse at the John S. Wright Forestry Center, 1007 North Tippecanoe County Road 725 West, West Lafayette, in Martell Forest, about 7.5 miles west of Purdue University. Photo by Weston Schempf.*

TABLE OF CONTENTS

PERSONNEL

- James (Jim) McKenna retired from the US Forest Service and HTIRC this summer. We thank Jim for all his hard work and dedication to the operational tree breeding program. His knowledge and presence will be missed, and we wish him success in his new ventures.

RESEARCH

- HTIRC Executive Committee approved funding four new research proposals that started July 2021 and aim to advance the goals of the HTIRC strategic plan (see table below).

Project Title	PI	Funding	Duration
Backpack system for high resolution forest inventory	Habib	$ 150,000	3 years
Testing efficacy of underplanting and enrichment plantings for stand regeneration in hardwood forests	Jacobs	$ 144,000	2 years
Indiana's Future Forests: Emptied niche occupation in an ash-less world	Saunders	$ 109,500	3 years
Better black walnut by "Breeding without breeding"	Woeste	$ 150,000	3 years

OUTREACH/EDUCATION

- This year PhD student Geoffrey Williams successfully defended his dissertation. Geoff has since moved on to a position with the USDA Forest Service. Congrats, Geoff!
- Several MS students successfully defended their theses this year. Congratulations to Sara Cuprewich, Ben Rivera, and Recep (Rich) Yildiz.

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.

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

INDIANA DEPARTMENT OF NATURAL RESOURCES, DIVISION OF FORESTRY: The Division's mission is to manage, protect and conserve the timber, water, wildlife, soil and related forest resources for the use and enjoyment of present and future generations, and to demonstrate proper forest management to Indiana landowners.

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

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.

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 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
Janis Gosewehr | Administrative Assistant
Lenny Farlee | Sustaining Hardwood Extension Specialist
Elizabeth Jackson | Engagement Specialist
Weston Schempf | Research and Communications Coordinator
Nathan Hilliard | Laboratory Manager
Patrick O'Neil | Genomics Laboratory Manager

PROJECT SCIENTISTS

Anna Conrad | US Forest Service, Plant Pathologist
John Couture | Entomology
Songlin Fei | Measurements & Quantitative Analysis
Ayman Habib | College of Engineering
Brady Hardiman| Urban Ecology
Joseph Hupy | School of Aviation and Transportation Technology, Purdue University
Douglass Jacobs | Forest Biology
Michael Jenkins | Forest Ecology
Shaneka Lawson | US Forest Service, Research Plant Physiologist
Jingjing Liang | Quantitative Forest Ecology
Carrie Pike | US Forest Service, Region 9 Regeneration Specialist
Michael Saunders | Forest Biology/ Ecology of Natural Systems
Guofan Shao | Forest Measurement and Assessment/GIS
Keith Woeste | US Forest Service, Molecular Geneticist
Mo Zhou | Forest Economics and Management

POSTDOCTORAL RESEARCH ASSOCIATES

Indira Paudel
Christopher Smallwood
Andrei Toca
Zhaofei Wen

GRADUATE STUDENTS

Molly Barrett | MS
Aziz Ebrahimi | PhD
Elias Bowers Gaffney | MS
Sayon Ghosh | PhD
Scott Gula | PhD
Yunmei Huang | PhD
Brianne Innusa | MS
Caleb Kell | MS
Bowen Li | MS
Alison Ochs | MS
Brande (Bee) Overbey | PhD
Minjee (Sylvia) Park | PhD
Sarah Rademacher | MS
Summer Rathfon | MS
Kelsey Tobin | PhD
Rebekah Dickens Ohara | PhD
Cameron Wingren | MS

TECHNICAL STAFF

Brian Beheler | Farm Manager
Don Carlson | Forester
Sarah Cuprewich | Research Assistant
Caleb Kell | Research Forestry Technician
Caleb Redick | Research Associate
James Warren | US Forest Service, Biological Scientist/Operational Tree Breeder
David Mann | Research Assistant
Rebekah Shupe | Research Associate

In the past year the HTIRC continued to adapt to the challenges of the pandemic to deliver on our mission, and this Annual Report details many of the ways the center advanced our strategic research, Extension and learning objectives. Through our project-based funding model, we are currently supporting 17 projects; four are new projects funded in 2021. The HTIRC Executive Committee reviewed and selected each one, and a special thanks goes to them for their vision and continued leadership and engagement. These research projects directly serve our strategic research objectives and reflect our commitment to meeting the needs of our stakeholders, and we look forward to funding additional projects in the coming year.

In this Annual Report we share progress reports on each of these projects. Our efforts and investments in integrated Digital Forestry (iDiF), led by Songlin Fei, have been acknowledged and rewarded by the university. In spring 2021, iDiF was recognized as part of the Plant Science 2.0 institute in the Purdue's Next Moves initiatives. The goal of iDiF is to leverage digital technology and multidisciplinary expertise to measure, monitor and manage urban and rural forests to maximize social, economic, and ecological benefits. The iDiF team currently has a total of 23 researchers, seven postdocs, and 29 graduate students, representing 12 departments/units within and outside Purdue University. The team has continued its growth in diverse research areas, focusing on inventory automation, disease and disturbance monitoring, and management optimization. Various research papers have been published and intellectual properties have been filed. The team has also increased its collaborations with government agencies, industrial partners, private companies, and other key stakeholders in the central hardwood region.

We were able to hold our annual HTIRC meeting in hybrid-fashion in October and enjoyed engaging with you and sharing the results of our funded projects. A highlight of the meeting was our field-tour that included live demonstrations of many of the technologies used in our digital forestry work. Thanks to all who joined us either in-person or online. I want to personally invite you to attend this year's meeting in the fall. Guidance and input from our stakeholders are critical to the continued growth of the HTIRC and research it supports.

This year we welcomed Rebekah Shupe as a research associate working with Carrie Pike and Songlin Fei to create a directory and subsequent digitization of living genetic trials across the eastern US. We also bid farewell to Jim McKenna, who served as the operational tree breeder for the HTIRC almost since its conception. Jim retired in July, and we thank him for his valuable contributions to our breeding and improvement efforts over the years. He has been missed. We wish him the very best in his retirement and future adventures.

As always, we remain steadfast in our commitment to connect our partners, collaborators, and stakeholders with the people, information, and products of the center. We continue to explore new ways to engage stakeholders and use technology to mobilize the knowledge generated by the center to a broad audience. In closing, I greatly appreciate the efforts of our advisory committee, staff, project scientists and students in supporting and delivering cutting-edge and relevant research and Extension products. I look forward to continue working together to advance the science and application of tree improvement, management, and protection of hardwood forests in the year to come.

HTIRC™
HARDWOOD TREE IMPROVEMENT
& REGENERATION CENTER

Matthew Ginzel
HTIRC Director

ACTIVITIES

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:

- John Brown *(Pike Lumber)*
- Dan Dey *(US Forest Service)*
- Dana Nelson *(US Forest Service)*
- Guillermo Pardillo *(ArborAmerica)*
- Jack Seifert *(Indiana DNR)*

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 was 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. Funding from NSF CAFS supports projects that address CAFS research themes as part of our HTIRC project-based funding model. In addition to the core funding 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, a member of the HTIRC Executive Committee, serves as our representative to the IAB.

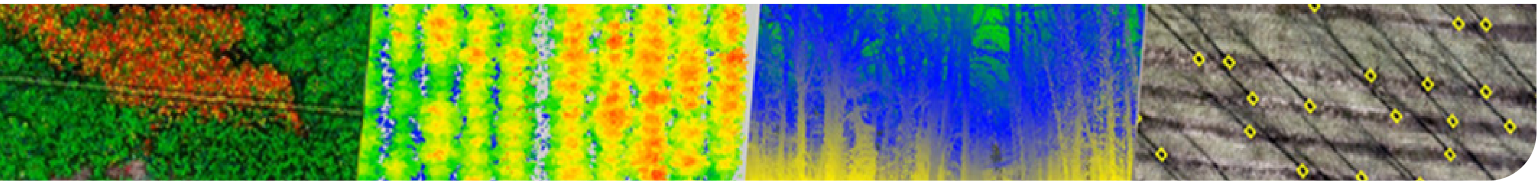
In CAFS Phase III, HTIRC Purdue participates in three collaborative research projects with partners across other CAFS university sites. The HTIRC Purdue site is leading a project related to using hyperspectral imaging to evaluate forest health risk, which aligns with two HTIRC-funded projects (PI John Couture). Another project involves assessing and mapping regional variation in site productivity, a project led by North Carolina State University, for which we are contributing from a funded HTIRC project on soil suitability indices for black walnut (PI Shaneka Lawson). The last project deals with intraspecific hydraulic responses of commercial tree seedlings to nursery drought conditioning, which is led by the University of Idaho site. The HTIRC Purdue site is participating with results for black walnut funded by a USDA NIFA grant (PI Douglass Jacobs). We expect to participate in additional projects as CAFS Phase III continues.

NSF CAFS website: https://iucrc.nsf.gov/centers/center-for-advanced-forestry-systems

Center for Advanced Forestry Systems

NSF

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 onboard 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 prevent 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.

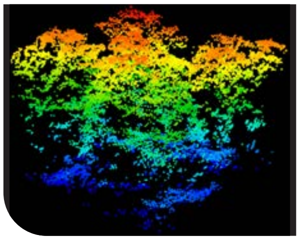
The overarching goals of Purdue's **iDiF Initiative** are: (1) to revolutionize forestry with an effective digital system for precision forest management that maximizes the social, economic, and ecological benefits of urban and rural forests, and (2) building globally competitive next-generation workforce 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:

- AI-assisted automated **M**easurement with multi-platform and multi-scale data
- IoT, Big Data, and Edge and Cloud Computing-enabled precision forestry
- Large-scale forest health (fire, disease, disturbance) **M**onitoring
- Workforce education of digitally-competent **M**indset (undergraduate and graduate)

Forests support over 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
- Sustainable workforce development and employment in rural America, narrowing the digital divide
- Educated workforce for the information age

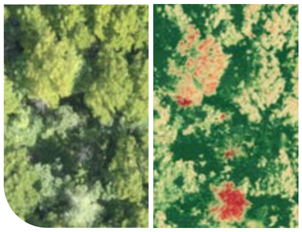
The iDiF Initiative is part of the Plant Science 2.0 of the Purdue Next Moves. The team consists of over a dozen faculty members from various nationally-ranked programs (Forestry and Natural Resources, Computer Graphics Technology, Electrical and Computer Engineering, Aviation Technology, Environmental and Ecological Engineering, Civil Engineering, and Information Studies) across multiple colleges. The team has various 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

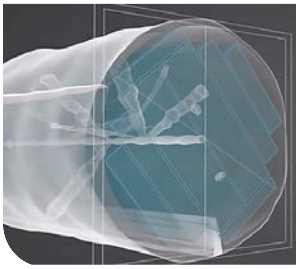
- AI-assisted automation of individual tree recognition and delineation
- Remote measurement of biometrics (size, biomass) in planted and natural forests



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

MONITOR STRESS EPIDEMIOLOGY

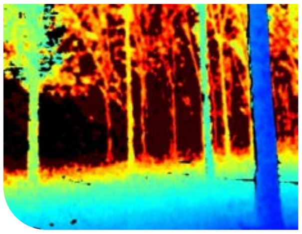
- Detection and tracking pest insect and pathogen incidence with machine learning on multi-temporal data
- Monitoring drought symptoms with multi-sensor platforms



Glass-view log from CT-scanning

PRECISION MANAGEMENT

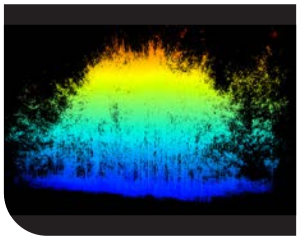
- Geo-referenced and image-assisted biometric evaluation for precision tree growth and yield modeling
- Log and lumber processing optimization with CT scanning



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

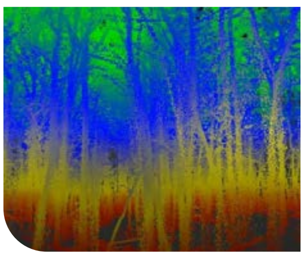
TREE HEALTH & QUALITY ASSESSMENT WITH LiDAR

- 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)



High-res LiDAR for tree inventory

LiDAR FOR HIGH-RESOLUTION FOREST INVENTORY

- Backpack/UAS system/platform and algorithms for fine-detail, automated measurements and trait characterization for forest plantations

2021 HTIRC-FUNDED RESEARCH GRANT UPDATES

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

INVESTIGATOR(S)

- **Shaneka Lawson,** *Research Plant Physiologist, USDA Forest Service (USDA-FS), Adjunct Assistant Professor, Purdue University (shaneka.s.lawson@usda.gov)*
- **James Warren,** *Biologist, USDA Forest Service*

PROJECT OBJECTIVES

Improving establishment practices of pure and mixed hardwood plantations by refining soil suitability indices for black walnut.

- Test the framework of the Wallace & Young (NRCS) black walnut suitability index at three black walnut planting sites.
- Intensively sample soils at three black walnut and three Northern red oak sites to obtain physiological data.
- Investigate and analyze soil data in conjunction with planted black walnut family data to look for trends.

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. 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.

APPROACH

STUDY SITE DESCRIPTIONS

- Seven ≥0.5 ha sites (4 black walnut, 3 northern red oak; 5 Indiana, 2 Michigan)
- Local temperature and precipitation data will be obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information, National Weather Service, and Climate.gov sites (https://www.ncdc.noaa.gov/cdo-web/, https://www.weather.gov/ind/, https://www.climate.gov/maps-data/dataset/past-weather-zip-code-data-table) to exclude effects from weather anomalies and other natural disasters (tornado, unprecedented flooding, etc.).
- Soils initially described using the NRCS Global Soils Regions map (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054013).
- The Natural Resources Conservation Service (NRCS) in Indiana Soils site, the Web Soil Survey and joint Purdue University – US Department of Agriculture integrative soils map for Indiana (https://www.nrcs.usda.gov/wps/portal/nrcs/in/soils/, https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx, https://soilexplorer.net/) will be used to classify soils.

MODEL EVALUATION

- The Wallace and Young model presumes black walnut tree heights can be used to predict soil depth.
- Cross validation will be used for model evaluation.
- Results from this study could have major implications for future forest management and plantation development plans.

SITE AND STAND DATA TO INCLUDE

- Height data and site characteristics such as pH, soil depth (divided by organic layer and horizon), soil texture, bulk density, and nutrient loads (N, P, K).
- Climate data (temperature and precipitation) and proximity to active crop fields.

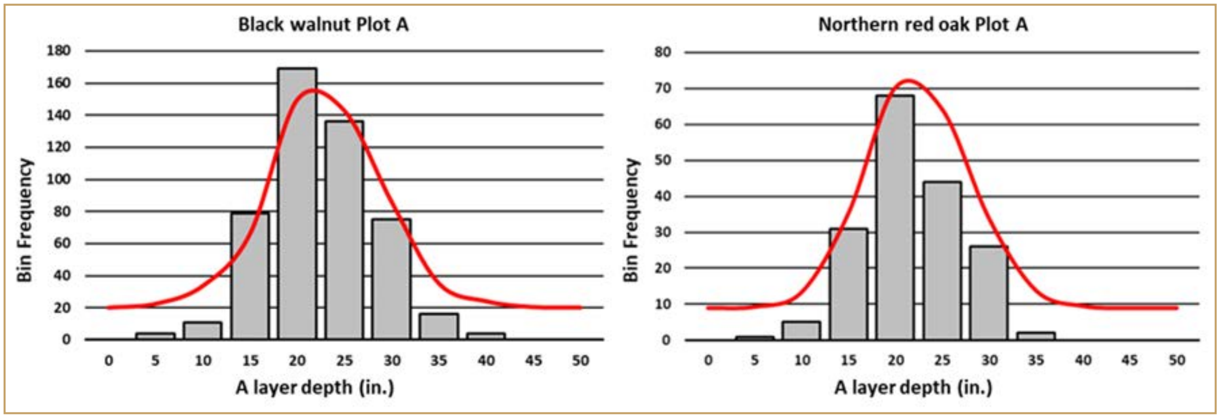
STATISTICAL ANALYSES OF TRAITS

- Independent and comparative site regression analyses
- Analyses performed in SAS or R (https://cran.rproject.org/web/packages/asremlPlus/index.html).

KEY FINDINGS / ACCOMPLISHMENTS

PROJECT PROGRESS

- All sites have been visited, with 100% of samples submitted for analysis*.
- Data from 5 sites (2-walnut, 3-northern red oak) have been received and graphed with GIS.
- All observed traits show variability between walnut and northern red oak.
- Data have been analyzed for standard distribution and bin frequency.
- Meetings to discuss manuscripts outlines have been conducted with several collaborators.



DISSEMINATION / EXTENSION EFFORTS

- Six oral presentations (1 NC State, 1 Walnut Council, 1 Alpha Kappa Alpha Sorority, Inc., 1 Soil Science Society of America (SSSA), 1 SEPAC, 1 Soil to potential collaborators (Forest Service - Northern Research Station)
- Three poster presentations (1 HTIRC, 1 American Society of Agronomy, 1 International Society for Microbial Ecology)
- One presentation to potential nationwide collaborators (CR-DEI Leadership (Washington Office, Forest Service (Northern & Southern Research Stations), various Southern Research Station University representatives)

FUTURE PLANS

DISSEMINATION / EXTENSION EFFORTS

- Continue performing comparative analyses of findings with walnut and northern red oak to poor, marginal, and good soil sites to provide proof of concept.
- Presentations: Northeastern Area Association of State Foresters Forest Utilization Committee, International Wood Collectors Society Great Lakes, and the Walnut Council (multiple states).
- Overlay new soil analyses with coarse soil maps from the United States Department of Agriculture Soil Conservation Service.

PARTNERS / COLLABORATORS

PARTNER AND STAKEHOLDER GROUPS

- Walnut Council, Tree Farm, Society of American Foresters, various forestry and woodland owner organizations and agencies

COLLABORATING INVESTIGATORS

- Carrie Pike, Regeneration Specialist, USDA-FS, Northeastern Area State & Private Forestry, FNR, Purdue University
- Lenny Farlee, Sustaining Hardwood Extension Specialist, FNR, Purdue University
- Jim McKenna, Operational Tree Breeder (Retired), USDA-FS
- John Kabrick, Research Forester, USDA-FS, NRS, Department of Agriculture, Food & Natural Resources, University of Missouri-Columbia
- Shalamar Armstrong, Assistant Professor of Soil Conservation and Management, Department of Agronomy, Purdue University
- Mary Beth Adams, Research Soil Scientist, Emeritus, USDA-FS, NRS, Morgantown, WV

USING TERRESTRIAL LASER SCANNING TO ASSESS TREE HEALTH AND QUALITY

INVESTIGATOR(S)

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

PROJECT OBJECTIVES

- Develop a suite of tools including affordable, off-the-shelf TLS 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.
- Evaluate the ability of TLS to reliably quantify tree and stand level indicators of quality and health.
- Share tools and methods with HTIRC researchers and stakeholders in trainings and workshops.

ABSTRACT

Work continued during 2021 to develop a workflow for processing terrestrial lidar data and extracting structural features indicative of tree health and quality. Funds were allocated to support Zhihang Song, a PhD student in ABE, in collaboration with Dr. Jian Jin. Zhihang led the development of this analytical workflow. Efforts in 2021 focused on refinement of the workflow to improve computational efficiency and speed by selecting the appropriate workflow architecture and optimizing algorithms and parameter sets to achieve the desired accuracy in less time.

Additional data was collected from two ages of walnut plantations at Martell Forest using the same terrestrial lidar instrument. These data were used to test the ability of the workflow to a) detect individual stems, and b) extract features of interest, including diameter, height, and height to first branch, all features that strongly influence quantity and quality of timber. The workflow proved extremely adept at identifying individual stems from a raw point cloud and produced structural measurements that were accurate to within the error of a human using conventional means.

In December 2021, Drs. Songlin Fei and Brady Hardiman hired a new postdoc, Dr. Heejoon (Dennis) Choi, to take over the project from Zhihang Song. Dennis is quickly getting up to speed and will have progress to report at the annual HTIRC meeting.

APPROACH

- We will develop methods to assess the health and quality of trees and to inventory stands using data acquired from TLS systems. The efficacy of these methods will be evaluated by comparing to conventional forestry mensuration techniques.
- Field Measurements: Our study will be conducted using HTIRC plantations of important hardwood species throughout Indiana. We will select plantation sites based on the availability of forest inventory data and existing assessments of health and quality. We will partner with HTIRC members and stakeholders to conduct additional field measurements within plantations using conventional methods and evaluation criteria to assess tree health and quality. Tree attributes (Table 1) will be measured with standard forest inventory tools (diameter tapes, clinometer, laser range finder, etc.) available in the Hardiman lab.
- Terrestrial Laser Scanner: TLS data will be acquired using a Lecia BLK360 Scanner (Lecia Geosystem AG), currently available in the Hardiman Lab. The scanner emits infrared laser pulses to measure distance from the scanner while it slowly rotates. The resulting point cloud can contain up to 80 million points each at sub-centimeter resolution (6mm accuracy at 10m); these scans will be used to produce a high-resolution digital rendering of each tree in a stand. The measurement speed of the scanner is less than 3 minutes for a full hemisphere scan at the highest resolution setting, including co-registered spherical color and thermal images, reducing time spent conducting field measurements. Early tests of the TLS system accuracy suggest an average difference of <5mm between TLS-based estimates of stem diameter and those obtained from a diameter tape. For comparison, multiple people using diameter tapes to measure the same tree often obtain values that differ by at least this much.

- We will collect TLS scans in both leaf-off season when foliage will not be an obstacle for measuring tree stem attributes, branch size, and top of the tree, and during the growing season, when we can observe tree health from leaves that reflect different amounts of energy based on health conditions. In addition to structural data obtained from the LiDAR capabilities of the BLK360, the instrument also has three calibrated digital cameras that allow it to collect panoramic, high-resolution hemispherical color images, and panoramic thermal images with an integrated infrared sensor. Traditional vegetation indices (such as NDVI and EVI) can be generated using these combined images; a tree health map will be developed based on tree characteristics such as leaf color and temperature, and crown condition.
- TLS Analytical workflow: The limiting factor in successful use of TLS technology to assess forest health and quality from stem to stand is in the extraction of meaningful information from the raw 3D point clouds that these instruments generate. We are refining an automated analytical workflow that will ingest 3D point cloud data from TLS systems and from it generate stand inventory data including height, stem numbers, diameter distribution, etc. Our longer-term goal is to expand this automated processing software to also calculate tree attributes that are indicative of health and which contribute to/detract from eventual timber quality.

KEY FINDINGS AND ACCOMPLISHMENTS

- New TLS data were acquired at Martell Forest in summer 2021 in walnut plantations of different ages and sizes.
- Our analytical workflow in development can, from an undifferentiated 3D point cloud, identify individual stems and estimate diameter, biomass, height, stem straightness, and taper (Figure 3). This workflow can quantify these features with accuracy that meets or exceeds conventional, manual methods while increasing replicability and reducing variation arising from repeat observations by multiple different people. We are working to refine this workflow to improve automation and ease of use and will continue adding capability to quantify new features indicative of tree health and quality.

FUTURE PLANS

- A key step moving forward will be to evaluate the capabilities of the workflow we have developed in this project relative to other workflows with similar goals. Drs. Ayman Habib and Jinha Jung are leading parallel efforts that have resulted in independent workflows with substantial similarities in output but significant differences in approach. Intercomparing of these various methods will allow selection of the parts of each that are most effective and integration into a single optimized workflow.

PARTNERS AND COLLABORATORS

- Ayman Habib, Professor, Civil Engineering, Purdue University
- Gordon McNickle, Assistant Professor, Botany and Plant Pathology, Purdue University
- Jian Jin, Associate Professor, Agricultural and Biological Engineering, Purdue University

NATURAL AND ARTIFICIAL REGENERATION GROWTH RESPONSE OF WHITE OAK ACROSS LIGHT AND UNDERSTORY COMPETITION GRADIENTS (YEAR 3)

INVESTIGATOR(S)

- **Mike Saunders**, *Associate Professor, Forestry and Natural Resources, Purdue University (msaunder@purdue.edu)*
- **David Mann**, *Research Assistant, Forestry and Natural Resources, Purdue University*
- **Molly Barrett**, *Research Assistant, Forestry and Natural Resources, Purdue University*

PROJECT OBJECTIVES

- Compare the interacting effects of prescribed fire and expanding group shelterwood systems on short-term natural regeneration response of oak species; and
- Compare the short-term effects of light levels and competition control on underplanted white oak of several controlled seed sources.

ABSTRACT

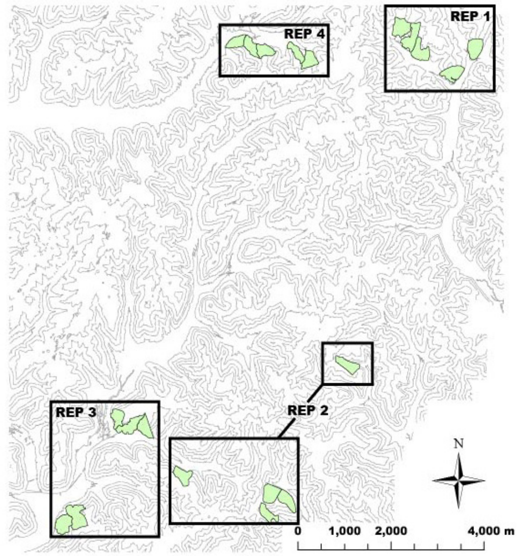


Figure 1.

Regeneration of white oak (Quercus alba) has long been problematic in the Central Hardwood Region. This has led to a pronounced imbalance in the age class distribution of many forests; white oak growing stock is projected to decline rather precipitously after peaking in the 2050s and 2060s (WOI Executive Committee 2021). New silvicultural approaches to naturally regenerate the species and well as development/refinement of cultural regimes to artificially regenerate the species are both needed to help offset the projected loss of white oak from our forests. This research documents both natural and artificial regeneration responses to gradients of light and understory competition gradients in a natural forest setting.

In 2015, a replicated trial of two expanding group shelterwood regeneration systems was installed across 8 sites (Reps 1 and 2; Figure 1) at the Department of the Navy's NSA Crane installation near Crane, IN.

Half of these sites received prescribed fire just prior to a winter 2015-16 overstory harvest. We documented 5-year growth responses using quadrats located on 400 permanent plots and 160 group-based transects during summer 2020. Preliminary analyses suggest that oak competitiveness is waning (Figures 2 and 3) compared to 2-year regeneration trends, likely due to increasing competition from mesic species and lack of prescribed fire applications during the intervening period between regeneration inventories.

Expansion of the group shelterwood study to 8 new sites in 2020 (Reps 3 and 4) provided an opportunity to quantify the growth responses of artificial white oak regeneration in a variety of growing conditions. After overstory harvests in winter 2020-21, we underplanted nearly 1,000 1-0 and 2-0 white oak seedlings, split among four seed sources (IN, IL, AR, and WI) in four plots lain across the boundaries of shelterwood groups. Seedlings were marked individually and fenced to prevent deer browsing. Each plot was then split into three to look at no weed control, 2-year weed control and 4-year weed control options. Very preliminary data after one growing season suggest minor differences among seed sources in survival, ground-line diameter growth and height growth; these seedlings will be monitored for at least 5 more growing seasons.

APPROACH

- Expand an existing silvicultural study and document longer-term natural regeneration patterns in response to prescribed fire and varying levels of overstory harvest.
- Collect white oak seed from multiple geographic sources to allow comparison of broad-scale climate impacts.
- Underplant 1-0 and 2-0 white oak stock into plots overlaying the silvicultural study, thereby creating a gradient of overstory light levels and understory competition levels (through active weeding).
- Track survivorship and growth of white oak seedlings over at least 5 years.
- Identify ideal combinations of residual overstory density/shade and duration of weed control that lead to successful underplantings of white oak.

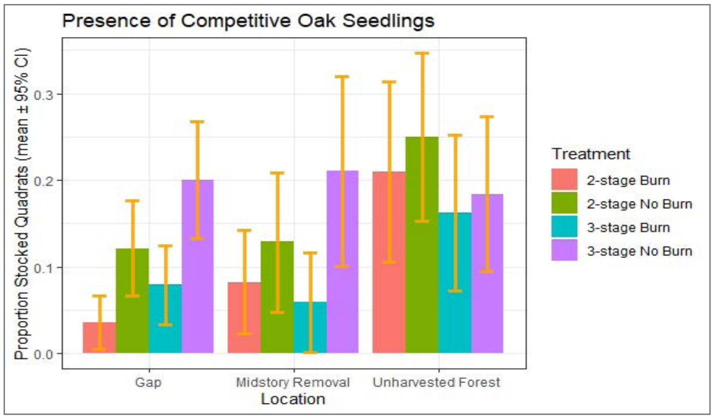


Figure 2.

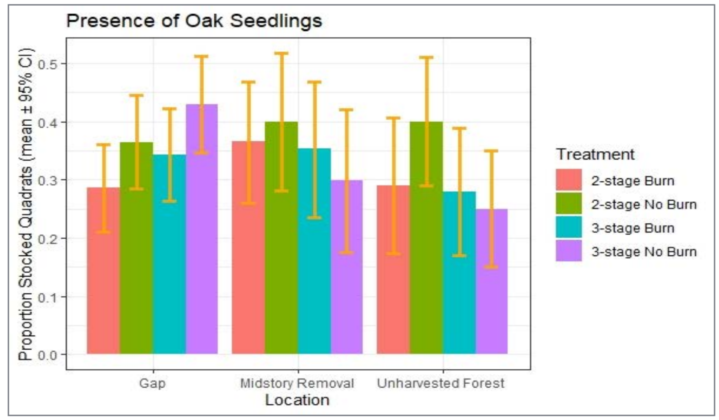


Figure 3.

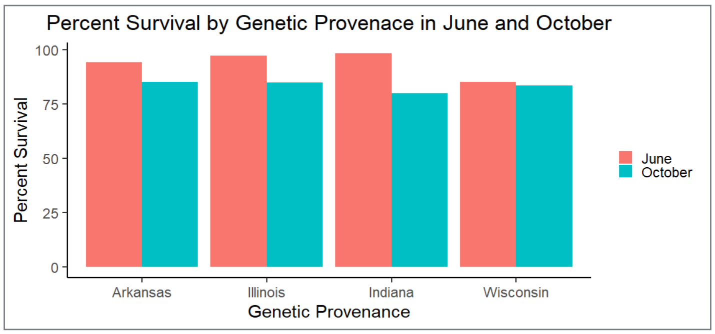


Figure 4.

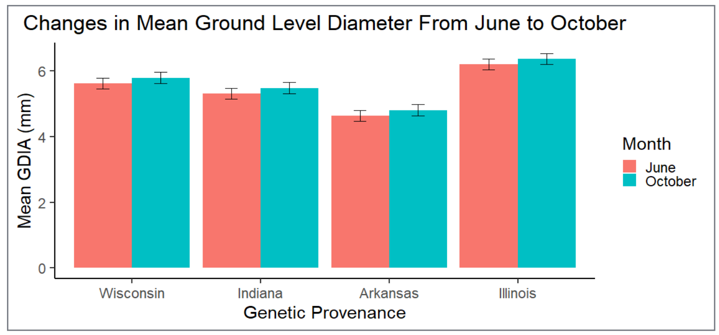


Figure 5.

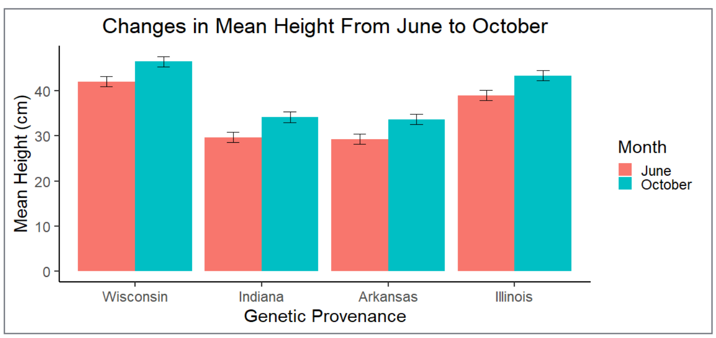


Figure 6.

KEY FINDINGS

Oak does not appear to be maintaining its stocking levels after 5 years post-harvest, directly conflicting with the results reported by Greenler and Saunders (2019). Oak stocking now ranges from 25-40% depending on treatment and location relative to the group opening (i.e., gap; Figure 2). Competitive oak seedlings, i.e., those seedlings likely to persist long-term, are even more restricted in stocking, peaking at 20-25% in unharvested forest matrix and within the 3-stage, no burn treatment (Figure 3). We did not detect strong differences among shelterwood types or with use of prescribed fire; the latter observation is somewhat expected since prescribed fire is useful for regeneration only when sustained (i.e., multiple applications). We will conduct further analysis to tease out differences among species and growing conditions before making final recommendations.

In regard to underplanting, survival is relatively high, exceeding 75% for all seed sources (Figure 8). However, one underplanting plot contributes nearly 42% of the total experiment-wise mortality; we may need to replant that plot with alternative stock if mortality is high over the winter. Seedling height (Figure 9) and ground-line diameter (Figure 10) increase slowly; height growth is generally 10-20% of initial seedling height and diameter growth is only 5-10% of initial diameter. White oak invests much of its photosynthate to root development after planting, so this is not surprising. We plan to analyze growth and survival in regard to weed control or light availability next year after more data collection.

FUTURE PLANS

- Conclude the analysis and prepare a manuscript of 5-year natural regeneration response of replicates 1 and 2 as part of a MS thesis (to defend in spring 2022).
- Maintain fencing and weed control treatments at the four experimental underplanted plots at NSA Crane and the one demonstration planting at Lugar Farm. Continue to monitor survival and growth; precisely measure light levels and competition ground cover during summer 2022 at both sites.
- Install biomass partitioning study at Lugar Farm using shade houses and competition from bush honeysuckle as treatments in spring 2022. This will be part of a new MS student's thesis, Eli Gaffney (BS, University of Missouri, 2021).

PARTNERS AND COLLABORATORS

A cooperative agreement with the U.S. Department of the Navy (Cooperative Agreement Number N62470-19-2-4014) and by the USDA-NIFA McIntire-Stennis Cooperative Forestry Research Program (Project: IND011557MS) also supports this work. We thank Rob McGriff and Trent Osmon, as well as the rest of the NSA Crane Environmental Team, for assistance with planting and fieldwork logistics.

Reference:

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.

WOI Executive Committee. 2021. Restoring sustainability for white oak and upland oak communities: an assessment and conservation plan. The White Oak Initiative (WOI), Washington, D.C. 62 p. Available at: https://www.whiteoakinitiative.org/assessment-conservation-plan (last accessed: Dec. 1, 2021)

PRODUCTIVITY-DIVERSITY RELATIONSHIPS IN HARDWOOD PLANTATIONS

INVESTIGATOR(S)

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- **John Couture**, *Assistant Professor, Entomology, Forestry and Natural Resources, Purdue University*
- **Lenny Farlee**, *Extension Forester, Forestry and Natural Resources, Purdue University*
- **Brady Hardiman**, *Assistant Professor, Forestry and Natural Resources, Purdue University*
- **Gordon McNickle**, *Assistant Professor, Botany and Plant Pathology, Purdue University*

PROJECT OBJECTIVES

- Characterize the productivity-diversity relationship in the mixed species experiment, partitioning productivity into leaves, wood, and roots
- Determine if and how functional traits that drive competitive interactions change with diversity and tree density
- Disseminate our findings to HTIRC stakeholders and professionals through Extension field days and programming

ABSTRACT

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.

SUMMARY OF ACCOMPLISHMENTS

In 2021, three HTIRC graduate students continued their research on this project. Kliffi Blackstone (PhD, McNickle) is evaluating leaf litter, tree growth, dendrochronology, and physiological traits. Madeline Montague (MS, Jacobs) studied belowground processes and successfully defended her MS thesis in March 2021. Taylor Nelson (MS, Couture) examined canopy processes and successfully defended her MS thesis in April 2021. We also continued collection of environmental data and 3D TLS repeat scans in 2021. Below, we summarize our specific accomplishments in 2021 related to the project objectives.

APPROACH

NET PRIMARY PRODUCTIVITY (NPP)

- Partitioning NPP into leaves, stems and roots.
- For contemporary stem growth, measurements of tree diameter at breast height (DBH) were taken in 2017-2021.
- To estimate growth back to the initial planting date in 2007, basal wood cores from three trees of each species per plot were taken, and dendrochronology is used to estimate NPP.
- The area of each tree ring as a basal area increment (BAI) was calculated and used to estimate the productivity-diversity relationship.
- Photosynthesis was measured to evaluate carbon assimilation among species combinations.

ROOT PRODUCTIVITY AND NON-STRUCTURAL CARBOHYDRATE (NSC) STORAGE

- Belowground productivity rates are quantified by isolating a single year of root growth using polypropylene mesh ingrowth cores.
- 112 ingrowth cores were installed and retrieved one year later.
- Root samples were extracted from soil, weighed, and ground with liquid nitrogen; the proportion of roots from each species in each soil core layer was quantified using quantitative PCR.
- Tracked NSC concentrations throughout American chestnut (leaves, branches, bole, and roots) to characterize seasonal NSC dynamics, and scaled concentration measurements to pool sizes using a custom-built allometric model.

Excavated a chestnut stump to build allometric model.

CANOPY PROCESSES

- Midseason green-leaf samples, in addition to weekly senescent leaf material, were collected. Samples were flash frozen, freeze dried, and milled into powder before being tested for nitrogen content via combustion reaction, and nitrogen resorption efficiencies (NRE) was calculated to determine the influence of biodiversity and competition.
- To estimate the influence of biodiversity and competition on canopy chemical profiles and insect feeding behavior, foliar tissue was collected at three time points (June, August, and October) in 2018 and 2019. All samples are flash frozen, freeze dried, and milled into powder and stored for further chemical analyses.
- To assess canopy damage, we imaged the October foliar collections and calculated the percent missing tissue. Insect material fluxes (frass, or fecal material, and green leaf material produced from incompletely consumed leaf material) were collected monthly from May to October.

Applying sheets to bucket to collect insect mediated material flux.

ENVIRONMENTAL EFFECTS

- Datalogger network was upgraded to a new model capable of uploading data in real time.
- Solar-powered dataloggers run a suite of sensors that measure light, air temperature, relative humidity, volumetric soil water, and soil water potential at 5-minute intervals, 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.
- Leica BLK360 terrestrial laser scanner (TLS) used to acquire a second round of 3D LiDAR point clouds from the center of each of 63 plots in the study design.

KEY FINDINGS/ACCOMPLISHMENTS

NET PRIMARY PRODUCTIVITY (NPP)

- The relationship thus far was not positive, as is common.
- Lack of a positive relationship between diversity and productivity in our plots creates an unexpected but testable hypothesis that there are not niche differences among our species.
- A relatively new branch of theoretical ecology called "modern coexistence theory" (MCT) revealed small niche differences among the three species used in this study.
- That discovery implies that density impacts competitive strategies, and this is heightened when compounded with diversity.

ROOT PRODUCTIVITY AND NON-STRUCTURAL CARBOHYDRATE (NSC) STORAGE

- Found that coarse roots were the largest and most dynamic NSC pool for chestnut.
- Additionally, there was a strong planting density × species composition interaction for chestnut root NSC pools, indicating that neighbor identity affects NSC storage.

CANOPY PROCESSES

- 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.
- 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.
- Results from 2018 and 2019 suggest that patterns of canopy damage, while low (although characteristic of damage levels of endemic insect herbivore populations), vary among levels of diversity and competition.

ENVIRONMENTAL EFFECTS

- Data are being processed in collaboration with Dr. Jian Jin (Purdue ABE) to derive structural features of interest including diameter, height, leaf area, and other metrics of tree growth and wood quality.

FUTURE PLANS

We will continue to estimate productivity using the NPP response variables. It is possible that the diversity–productivity relationship may change through time. The current 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. We can then use this knowledge to develop recommended species mixes that would increase timber production.

To further evaluate NPP, we have designed two new trials that complement the experiment at Martell Forest. The first was installed in spring 2021 across 6 acres at Herrmann Reserve, with eight hardwood tree species planted at four densities (1m x 1m, 2m x 2m, 3m x 3m, and open-grown). The second is a new greenhouse project to begin in spring 2022 using annual Indiana native plants. It will follow a comparative design to that of Martell, yet use of annual plants will allow us to analyze how the P-D relationship should affect growth patterns and biomass. These trials will provide an opportunity to examine how these species compare to the Martell results in terms of coexistence using the Modern Coexistence Theory.

One of Madeline Montague's MS thesis experiments will be published in Forest Ecology and Management in 2022. We will publish additional papers from this research over the coming years.

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

INVESTIGATOR(S)

- **Michael Jenkins**, *Professor, Forestry and Natural Resources, Purdue University (mjenkins@purdue.edu)*
- **Pierre-Luc Chagnon**, *Assistant Professor, Université de Montréal, Institut de Recherche en Biologie Végétale*
- **Lenny Farlee**, *Extension Specialist, Forestry and Natural Resources, Purdue University*

PROJECT OBJECTIVES

The overall objective of this research project is to determine the role of pathogens and AM fungi in driving or inhibiting Lonicera invasion in hardwood forests. Our specific objectives are:

- Objective 1: Predict soil biotic characteristics that favors bush honeysuckle (Lonicrera maackii) invasion
- Objective 2: Determine the sharing of belowground pathogens and arbuscular mycorrhizal fungi between bush honeysuckle and native plant species
- Objective 3: Measure nutrient transfer from bush honeysuckle to native seedlings as a function of season of treatment.

ABSTRACT

Although our study has been delayed by the closing of the US-Canada border, we have moved forward toward meeting our study objectives. Experiments have been completed to address objective 1, and DNA extraction has begun to examine the relationship between fungal associates and the belowground growth of bush honeysuckle. Because co-PI Chagnon was unable to travel to Purdue to initiate the experiment for objective 2, he initiated the field-based experiment in southern Ontario, where bush honeysuckle and associated native hardwood tree

species occur, by collecting roots from all species for extraction of fungal DNA. Seeds of native species were collected in Tippecanoe County, Indiana. These seeds will be germinated and seedlings will be inoculated with extract from the southern Ontario samples. Experimental work for objective 3 will move forward at Purdue during summer 2022, pending access across the US-Canada border. Our initial results have revealed that long-term invasion by bush honeysuckle is not associated with a fungal community adapted to exploit the presence of the invader. Overall, we observed few pathogens at any site, but arbuscular mycorrhizal colonization was high across honeysuckle and associated hardwood trees.

APPROACH

- Objective 1: Bush honeysuckle seedlings grown from seed collected on Purdue FNR properties were germinated and exposed to inoculum from soils of forests with differing invasion histories (Figure 1). Fungal species are currently being identified with Illumina MiSeq. The presence of these fungi will be correlated with belowground growth of bush honeysuckle. Data will be available by the end of February 2022, at which time lab personnel at Université de Montréal will begin analyses.

Figure 1. Left: germinating bush honeysuckle seeds. Center: bush honeysuckle seedlings, two weeks post transplanting. Right: white oak acorns collected to conduct experiment to meet objective 3.

- Objective 2: Because sampling in Indiana has been postponed until 2022, bush honeysuckle and neighboring woody plants were sampled in Hamilton, Ontario, Canada, at the Royal Botanical Garden during October 2021. Roots have been washed and frozen prior to the extraction of DNA from individual root fragments to (1) identify plants to species and (2) to then pool samples from identified plant species and evaluate the whole plant-fungal interaction network, allowing us to evaluate potential spillover of fungi species associated with bush honeysuckle onto natives through shared pathogens, or facilitation through shared symbionts. Seeds from three ectomycorrhizal (white oak-Quercus alba, northern red oak-Quercus rubra, and pignut hickory-Carya glabra), four arbuscular (white ash-Fraxinus americana, sugar maple-Acer saccharum, honey locust-Gleditsia triacanthos, and black walnut-Juglans nigra) tree species for the plant-soil feedback experiment were collected in Tippecanoe County, Indiana, in fall 2021. We have developed germination protocols to produce seedlings for the feedback experiment. Following the completion of the experiment, molecular analysis to identify fungal species from root samples will be conducted, producing results in April-May 2023.

KEY FINDINGS

OBJECTIVE 1

- Early results suggest that a longer Lonicera invasion history does not result in a fungal community adapted to exploit the resources offered by honeysuckle. Honeysuckle growth performance did not decline with longer occupation of the site by honeysuckle.
- This lack of a negative effect on honeysuckle does not result from a balanced increase in pathogens and mycorrhizal symbionts: we observed very little non-mycorrhizal fungal colonization at most sites. This contrasts with other invasive plant species, such as garlic mustard (Alliaria petiolata), where there is a noticeable local adaptation of microbial communities to the invader.
- Arbuscular mycorrhizal colonization was high in all experimental plants, indicating the importance of the nutritional symbiosis for honeysuckle, and its high potential to establish mycorrhizal networks with neighboring arbuscular trees, such as sugar maple and black walnut.
- We observed little evidence of pathogens, with the exception of one individual extracted in Ontario (Figure 1). Molecular data will tell us more, but so far we have little evidence that honeysuckle carries diseases compatible with neighboring trees.

Figure 2. Visible infection within stem vascular tissue of a honeysuckle shrub extracted in southern Ontario. The pathogen, if systemic and found in roots (typically the case for vessel-infecting fungi), could be identified by next-generation sequencing.

FUTURE PLANS

- Work will continue to complete experiments and molecular work for Objective 2.
- For Objective 3, we are planning to conduct a field experiment in Indiana in summer 2022, with two site visits by co-PI Chagnon. Conducting this experiment in Indiana will depend on the ability to travel from Canada. Another avenue would be to conduct a proof-of-concept study in Montreal using a growth-chamber experiment until travel to Indiana becomes possible.

TREE INVENTORY WITH AERIAL REMOTE SENSING

INVESTIGATOR(S)

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

PROJECT OBJECTIVES

- 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.
- 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.
- 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.

ABSTRACT

Sustainable forest management and precision tree improvement require detailed inventories of tree quantity and quality to support decision making processes. Accurate forest inventory information can significantly impact the potential for forest resources to meet economic and ecological needs. Forest inventory data is currently collected using manual field sampling techniques, often relying on observations by trained experts, introducing substantial sources of error and reducing reproducibility of data collection effort. Recent technological advances offer new methods and techniques that can increase the accuracy of tree quantity and quality measurements, and are cheaper and faster than conventional approaches. As part of the integrated Digital Forestry (iDiF) initiative, we propose to revolutionize forest inventory by developing methods that take advantage of recent advances in aerial remote sensing technologies. Specifically, we plan to (1) develop tools for automated individual tree delineation and biometric measurement for hardwood forests using freely available low-density aerial LiDAR and (2) develop user-friendly analytical methods to catalyze usage of unmanned aerial systems (UAS) or drone remote sensing for rapid tree inventory by forestry industry professionals. Products from this project can provide forest and plantation managers with much-needed information to improve hardwood forest management and improvement. The project will have strong potential impacts on the ecological health and economic profitability of forest ecosystems across Indiana, contributing to the development and sustainability of rural communities. The project will also help to build capacity in HTIRC's Digital Forestry initiative, allowing HTIRC to become a leader in this field.

APPROACH

LiDAR-based tree measure: We used a two-step segmentation procedure to delineate trees with low- density LiDAR: (1) identifying individual tree markers by local height maxima detection; and (2)applying marker-controlled watershed segmentation for tree crown delineation.

Orthophoto-based tree measure: A visible-band sensor mounted on a DJI Phantom 3 Advanced multi-rotor aircraft was used for the airborne data acquisition. Captured images were combined to form a true orthophoto mosaic of the forest surveyed at a spatial resolution of 2.5 cm per pixel. A 3D digital surface model (DSM) was then created based on the orthophoto mosaic using photogrammetry software Pix4D.

SUMMARY OF ACCOMPLISHMENTS

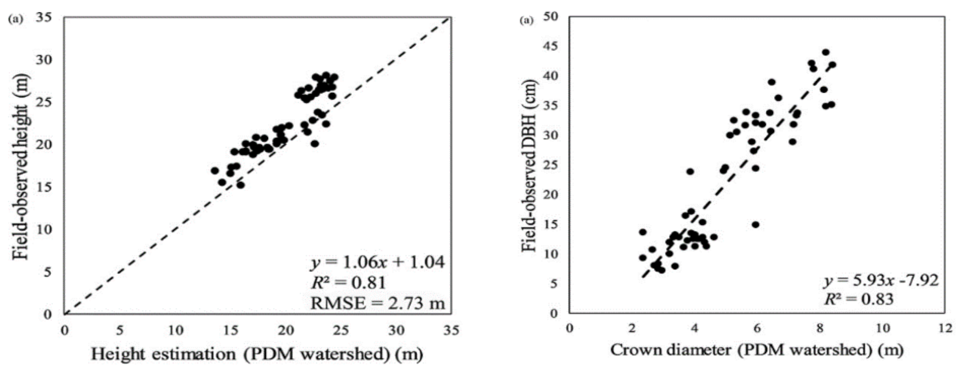
Two efforts have been made related to low-density LiDAR-based tree delineation. The first is to test the delineation of plantation trees with low-density LiDAR. We have successfully developed an algorithm to delineate a 60-year-old red oak plantation (Shao et al. 2018) and connected the relationship between aerial and terrestrial LiDAR (LaRue et al. 2020). The second is to test the low-density LiDAR delineation in natural stands, which has been proven to be difficult at the individual tree level but has great implications at the plot-level, especially in height measurement. We have developed a statewide canopy height model for Indiana. A manuscript on this topic, led by the postdoc funded by the project, has been submitted to Remote Sensing for review.

Significant progress has been made regarding the effort of using UAS orthophotos. We have developed an algorithm along with a website for UAS orthophoto-based tree delineating for plantation forest, along with a manuscript (Miller et al. 2021). We also recently made a breakthrough in successfully creating a 3D cloud of trees, which allows the identification and measurement of deciduous trees in natural forests.

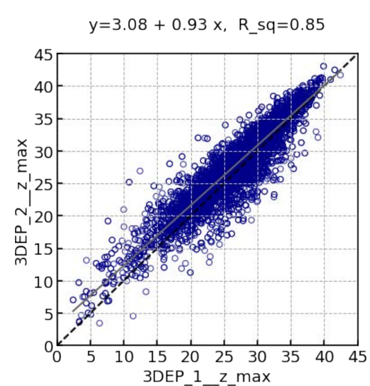
Research findings have been disseminated through publications, invited and contributed presentations, and stakeholder meetings. More importantly, thanks to the support from HTIRC on this and other projects, the iDiF initiative has garnered wide interest within and outside Purdue and continued its growth. The iDiF initiative has been selected as part of the Plant Science 2.0 within Purdue's Next Moves for five years. Moreover, the team has developed a $10M grant to USDA SAS program. Although it was not selected for funding, the grant was well received and was encouraged for resubmission for the coming funding cycle.

KEY FINDINGS/ACCOMPLISHMENTS

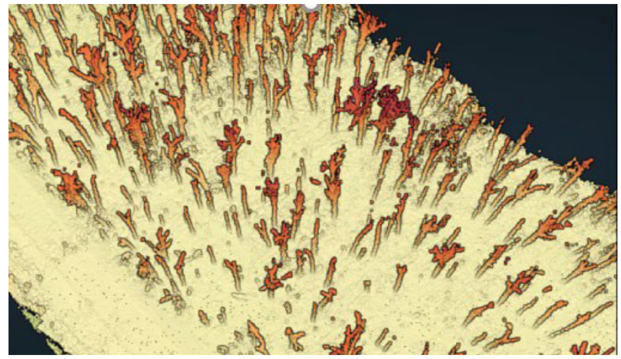
1. Low-density LiDAR-based plantation delineation is possible and with high accuracy for older plantations (Shao et al. 2018)



2. Low-density LiDAR can provide accurate tree height measure (Oh et al. under review in Remote Sensing)



3. Orthophoto-based tree delineation in natural forest is also feasible but more research is needed (a 3D point cloud of McCormick Woods)



4. The iDiF initiative has gained significant momentum. The team now has over 18 PIs 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.

- Website. We have developed a new website (https://digitalforestry.org/) highlighting the team and ongoing project.
- Data Portal. We have developed a web portal (https://lidar.digitalforestry.org/) to host and disseminate remote sensing data.
- Plant Science 2.0. We have been selected as part of the Purdue Next Moves.
- Forbes Ag Tech Summit. We were invited to present iDiF at the 2019 Forbes Ag Tech Summit to various digital ag companies and potential investors in 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.

FUTURE PLANS

We will continue the research topic and to disseminate our findings according to our plan. The COVID-19 pandemic has negatively impacted the research progress. An extension will be requested.

PARTNERS/COLLABORATORS

- Joseph P. Hupy, *Associate Professor, School of Aviation and Transportation Technology, Purdue University*
- Joey Gallion, *Forest Inventory Program Manager, Indiana DNR*
- Ayman Habib, *Professor, Civil Engineering, Purdue University*
- Jinha Jung, *Assistant Professor, Civil Engineering, Purdue University*

CHARACTERIZING ABIOTIC AND BIOTIC TREE STRESS USING HYPERSPECTRAL INFORMATION

INVESTIGATOR(S)

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

PROJECT OBJECTIVES

- Determine the ability of hyperspectral data to provide information related to tree status in response to abiotic and biotic stress
- Assess the reliability of hyperspectral information to scale from leaf, to tree, to stand level measurements
- Evaluate the validity of hyperspectral data to characterize stress responses over different spatial scales in different geographic locations.

ABSTRACT

Monitoring forest health is crucial to understanding function and managing productivity of forest systems. However, traditional estimates of tree health are time-consuming and challenging to collect because of the vertical and spatial scales of forest systems. This study evaluated the ability of a novel application of

hyperspectral data to estimate foliar functional trait responses to multiple biotic and abiotic stressors and to classify different stress combinations. In a greenhouse environment, we exposed one-year-old black walnut (Juglans nigra) and red oak (Quercus rubra) seedlings to multiple stress factors, alone and in combination. We collected reference measurements of numerous leaf physiological traits and paired them with spectral collections to build predictive models. The resulting models reliably estimated most black walnut and red oak leaf functional traits with external validation goodness-of-fit (R2) ranging from 0.37 to 0.90 and normalized error ranging from 7.5% to 18.3%. Spectral data classified different individual stress groups well, but the ability of spectral data to classify stress groups depended on if the stress events were applied individually or in combination. High-dimensional spectral data can provide information about plant stress, improve forest monitoring in future predicted environments, and ultimately aid in management efforts in forest systems.

APPROACH

- Exposed young, potted trees of black walnut and red oak to combinations of water, nutrient, salt stress, pathogen inoculation (Geosmithia morbida, walnut only) and insect feeding (Actias luna, walnut only).
- Collected multiple physiological, anatomical, and chemical reference measurements.
- Built predictive models using paired spectral and reference data and used machine learning classification algorithms to cluster trees into stress categories based on spectra alone.
- Collected leaf, UAV, and manned aircraft hyperspectral data in a mixed planting containing American chestnut with variable levels of chestnut blight to determine how well predicted stress responses can scale across measurements (i.e., leaf, plot, stand).
- Collected stress responses of Quercus to combined drought and ozone stress (through collaboration with University of Pisa in Italy).

KEY FINDINGS/ACCOMPLISHMENTS

- Tree chemical, physiological, and anatomical stress responses can be estimated using hyperspectral data (Figs. 1, 2, and 3).
- Spectral data can classify water and nutrient stress (Fig. 4) and fungal inoculation (Fig. 5) prior to the onset of visible symptoms. Although for fungal classification, responses depend on other environmental factors and time.
- Ozone stress can be detected using spectral data prior to the onset of visible symptoms.

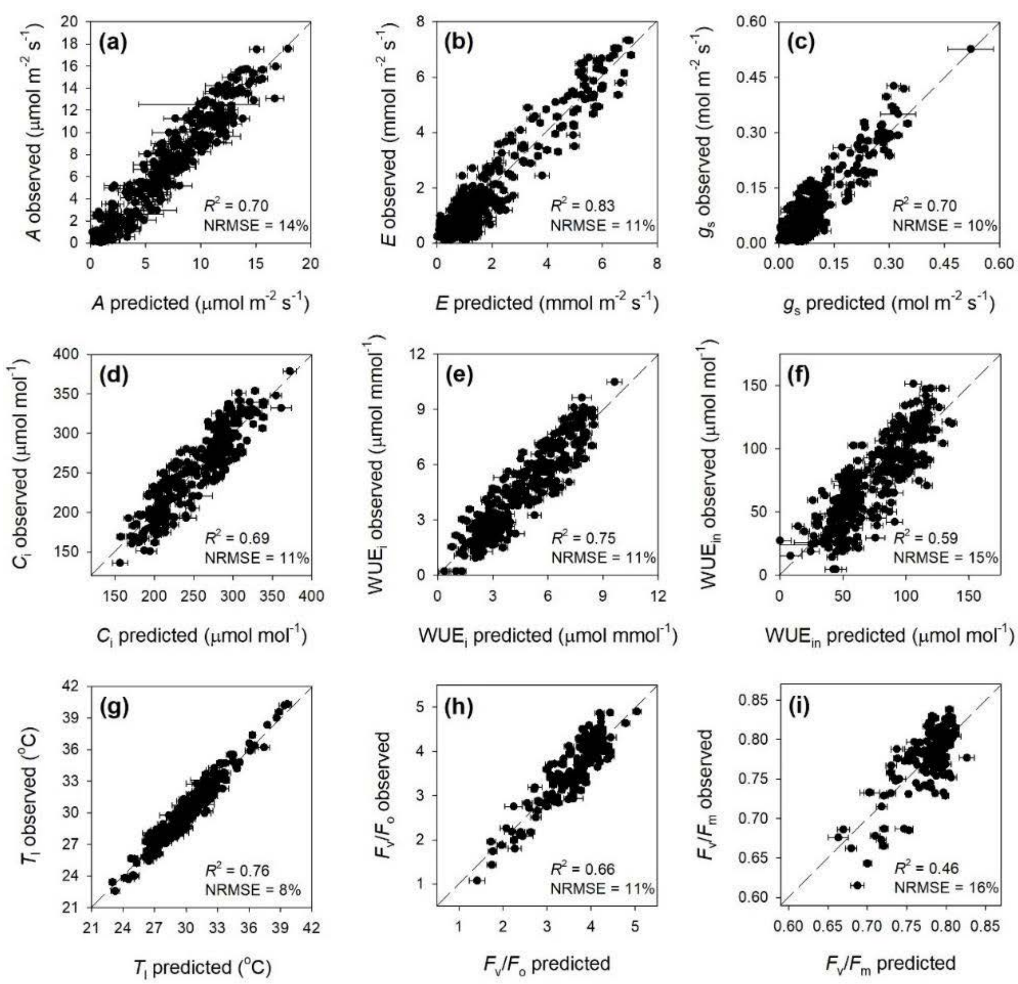


Figure 1. Observed vs. predicted values of leaf traits related with gas exchange parameters and chlorophyll florescence for black walnut and northern red oak exposed to various stressors. Error bars for predicted values represent the standard deviations generated from the 500 simulated models. The dashed line shows 1:1 relationship.

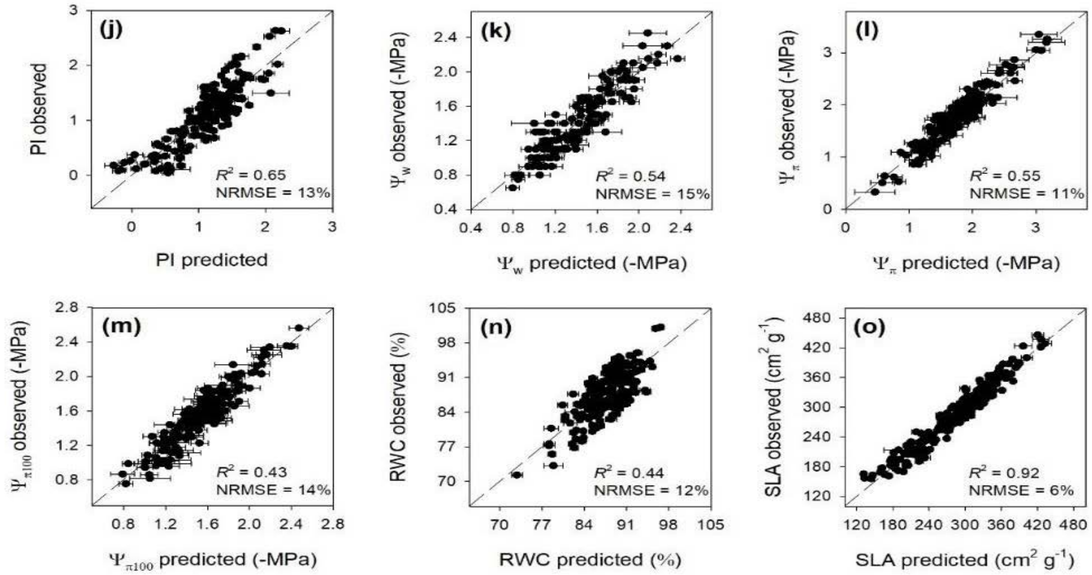
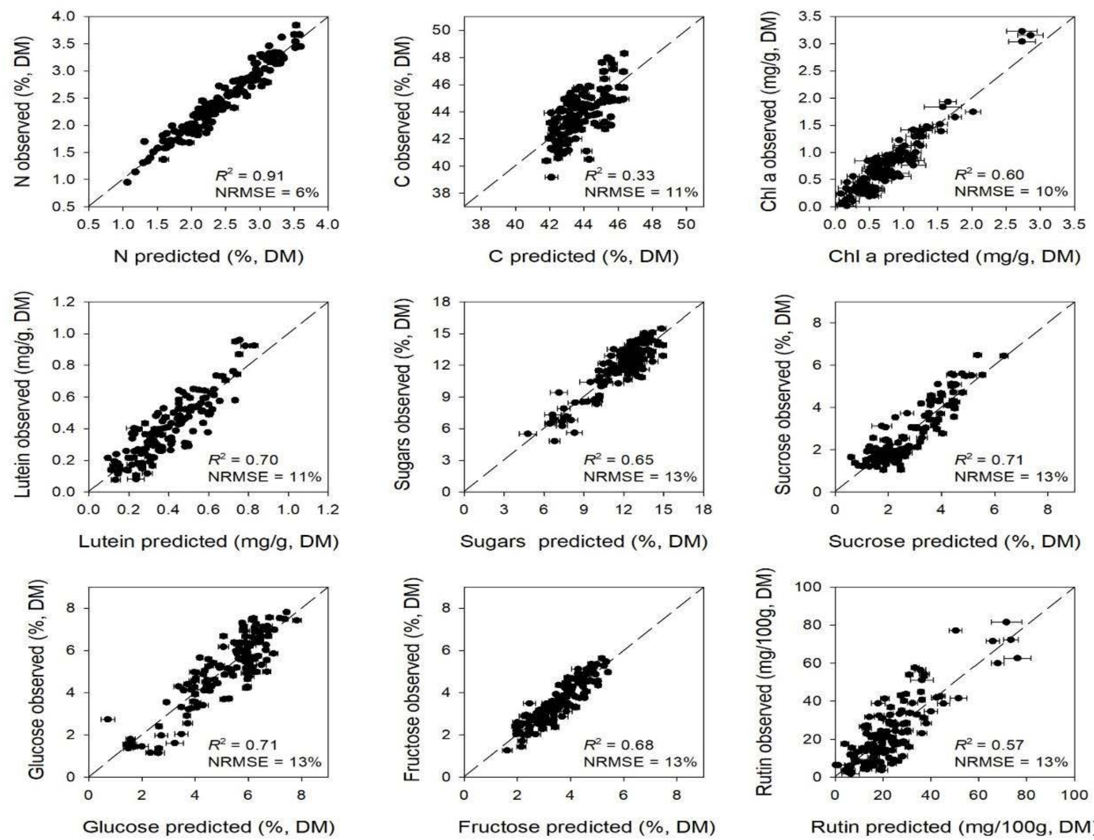


Figure 2. Observed vs. predicted values of leaf traits related with water status for black walnut and northern red oak exposed to various stressors. Error bars for predicted values represent the standard deviations generated from the 500 simulated models. The dashed line shows 1:1 relationship.



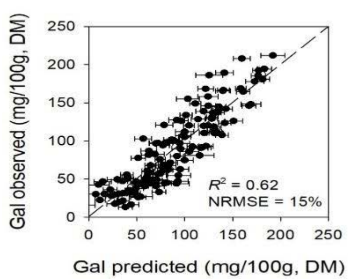


Figure 3. Observed vs. predicted values of leaf chemical composition of black walnut and northern red oak exposed to various stressors. Error bars for predicted values represent the standard deviations generated from the 500 simulated models. The dashed line shows 1:1 relationship.

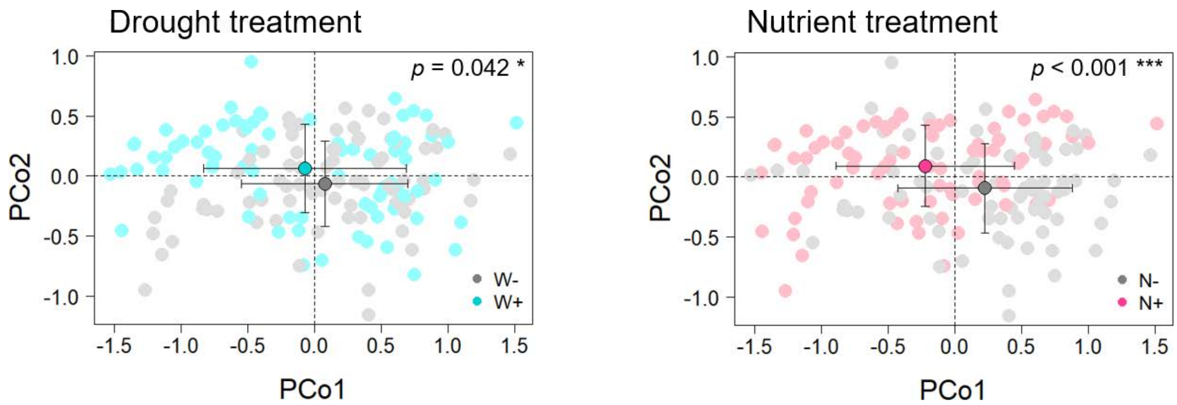


Figure 4. Scores (mean ± standard error) for the first and second components from principal coordinates analysis (PCoA) of reflectance data (400–2400 nm) collected from walnut leaves in 2018, showing the ability of spectral data to discriminate control (blue circle; W+) versus black walnut with drought stress (grey circle; W-) in the left panel and control (pink circle; N+) versus black walnut with nutrient deficiency stress (grey circle; N-) in the right panel. P-values from permutational analysis of variance for the effects of the drought and nutrient deficiency stress on full range (400–2400 nm) reflectance profiles of walnut leaves are shown in the top-right corners of panels.

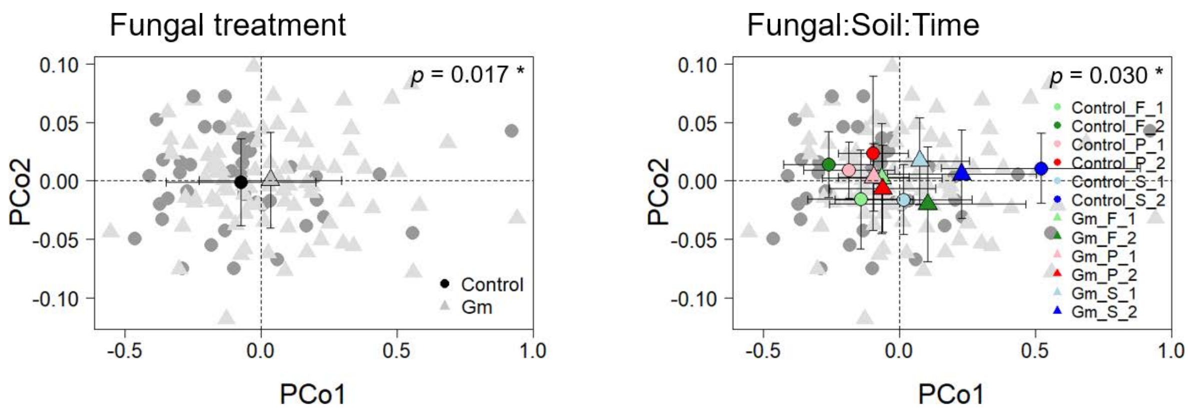


Figure 5. Scores (mean ± standard error) for the first and second components from principal coordinates analysis (PCoA) of reflectance data (400–700 nm) collected from walnut leaves in 2018, showing the ability of spectral data to discriminate control (black circle; Control) versus black walnut inoculated with the fungus Geosmithia morbida (grey triangle; Gm) in the left panel and the interactions among fungal treatment (circle; Control vs. triangle; Gm), soil type (green; forest vs. red; plantation vs. blue; sterile soil) and time length after fungal infection (light; 1 vs. dark color; 2) in the right panel. P-values from permutational analysis of variance for the effects of the fungal infection, soil types, and time on reflectance profiles (400–700 nm) of walnut leaves are shown in the top-right corners of panels.

FUTURE PLANS

- Graduate student Sylvia Park will write complete manuscript communicating outcomes from data presented in figures for a peer-reviewed publication. She will also continue to analyze data from other studies.
- Compare and analyze leaf, UAV, and airborne spectral data to assess scalability of spectral data across platforms.

PARTNERS/COLLABORATORS

- University of Pisa, Italy

2020 HTIRC-FUNDED RESEARCH GRANTS

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

INVESTIGATOR(S)

- **Mo Zhou,** *Associate Professor, Forestry and Natural Resources, Purdue University (mozhou@purdue.edu)*
- **Mike Saunders***, *Associate Professor, Forestry and Natural Resources, Purdue University*
- **Jingjing Liang**, *Assistant Professor, Forestry and Natural Resources, Purdue University*
- **Jim Warren**, *Biological Scientist, USDA Forest Service*
- **Lenny Farlee**, *Sustaining Hardwood Extension Specialist, Purdue University*
- **Elizabeth Jackson**, *Executive Director, Walnut Council/IFWOA, Engagement Specialist, Purdue University*

** Co-PIs Saunders and Ghosh joined the project in Sept. 2021.*

PROJECT OBJECTIVES

- Developing the first spatially explicit plantation growth & yield model for black walnut and red oak.
- Simulating and analyzing various thinning frequencies, intensities, and patterns.
- Quantifying the cost, return, and effectiveness of different thinning schedules.
- 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 investment analyses.

ABSTRACT

This project aims to provide sound scientific evidence and user-friendly tools to help promote better forest management decisions on hardwood plantations of black walnut and northern red oak. To supplement the existing HTIRC database, new measurements of diameter at breast height (DBH), height, and crown radius were completed on selected HTIRC plots. Models of optimal stand establishment within the first 10 years have been developed for both species. It is demonstrated that the best strategy to establish a black walnut plantation at the lowest cost requires an initial planting density of 6 feet by 7 feet (henceforth, 6 x 7) combined with herbicide for the first year and fencing. For a red oak plantation, the best strategy is to start with a density of 6 x 7, apply herbicide for the first three years, and put up fences. Next, we have estimated a growth model of black walnut trees between years 10 and 18, considering inter-tree competitions and forest edge effects. We find that a tree on the perimeter rows grows 0.30 cm (0.12 in.) in DBH more per year than the interior trees. Under different scenarios of survival rates and planting densities, we have started to simulate the effects of multiple thinning strategies on growth till the stand age reaches 18 years. For the remainder of the project, we plan to extend the simulation till the end of a commercial rotation while introducing stochastic environmental disturbances effects that may affect tree survival and competition. Finally, we will convert the simulator, which has been programmed in R, to an Excel-based Extension tool and complete a user's manual.

APPROACH

- Developing a nonlinear multi-stage model of stand establishment that minimizes establishment costs while ensuring free-to-grow status by year 5, and crown closure by year 10.
- Developing a spatially explicit model describing the individual tree growth subject to inter-tree competition and edge effects.
- Using stochastic simulations to understand the impacts of different thinning strategies under different scenarios of planting densities and survival rates.

KEY FINDINGS

- A black walnut plantation can attain crown closure in year six at the lowest cost ($4,540/ha) with a 6 x 7 spacing, herbicide application for the first year, and fencing. For red oak, the minimum-cost option ($5,371/ha) which achieves crown closure in year 10 requires a planting density of 6 x 7, herbicide application for the first three years, and fencing (Figure 1).

- Growths of the nearest eight neighbors of a tree, when weighted by their Euclidean distances, provide the most parsimonious formulation in capturing inter-tree competition.
- Significant predictors of annual diameter growth between years 10 to 18 include the initial tree DBH, forest edge effects, distance-dependent neighborhood competition, and the initial tree age (Table 1).
- Significant edge effects exist up to 3 rows and 3 trees from the non-forested edge. A tree on the perimeter rows, grows 0.30 cm (0.12 in.) in DBH more per year than the interior trees, between years 10 to 18.

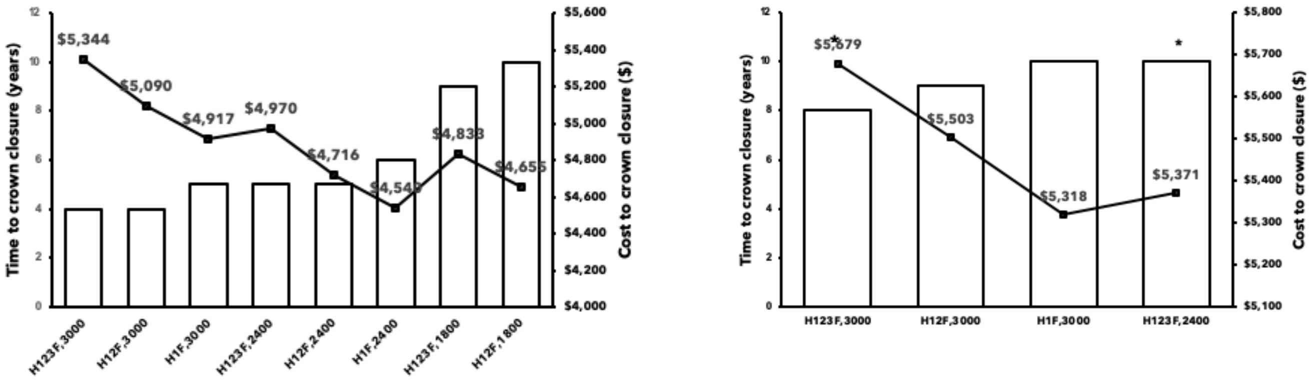


Figure 1 (Above: black walnut. Below: red oak) Treatments that achieve crown closure against time; costs for establishment on the secondary axis (right); all presented treatment density combinations (x-axis) are free to grow by the fifth year for black walnut and the ones marked with an asterisk (*) for red oak; Planting densities, noted as 3000 (6x6), 2400 (6x7) and 1800 (8x7) tree per ha achieve crown closure for different combinations of herbicide for one growing season and fencing (H1F), herbicide for two growing seasons and fencing (H12F), herbicide for three growing seasons and fencing (H123F); Note: Cost not to scale, provided for illustration purposes only.

Table 1. The estimated model of the annual growth in tree DBH (in cm) of black walnut trees. Edge_Dummy = 1 if the tree is in the forest edge boundary (within 3 rows and 3 trees from the non-forested edge). Hegyi'st represents Hegyi's index, an indicator of distance-dependent neighborhood competition.

	DBH Annual Increment (in cm $year^{-1}$)		
Predictors	*Estimates*	*Confidence Interval*	*p*
(Intercept)	0.220	-0.158 – 0.598	0.253
DBH_t	0.053	0.032 – 0.074	<0.001
Edge_Dummy (0/1)	0.309	0.215 – 0.403	<0.001
$Hegyi's_t$	-0.135	-0.232 – -0.037	0.007
Age	0.158	0.047 – 0.269	0.005
Observations	316		
R^2 / R^2 adjusted	0.444 / 0.437		

FUTURE PLANS

- Extend the simulations to the end of a commercial rotation to understand the impacts of different thinning strategies on growth and yield.
- Introduce stochasticity in model parameters due to environmental disturbances to investigate their impacts on tree competition and subsequent growth.
- Parameterize an Excel-based financial calculator with the completed estimations and simulations.
- Extend the financial calculator for investment profitability under different scenarios of cost-share programs.
- Complete a user's manual for the financial calculator.

PRECISE QUANTIFICATION OF FOREST DISTURBANCES WITH UAS

INVESTIGATOR(S)

- **Joseph P. Hupy**, *Associate Professor, School of Aviation and Transportation Technology, Purdue University (jhupy@purdue.edu)*
- **Songlin Fei**, *Professor, Forestry and Natural Resources, Purdue University*
- **Jarred Brooke**, *Extension Wildlife Specialist, Forestry and Natural Resources, Purdue University*
- **Guofan Shao**, *Professor, Forestry and Natural Resources, Purdue University*

PROJECT OBJECTIVES

- 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 at 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.

ABSTRACT

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 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 to rapidly, efficiently, and cheaply inventory trees remotely for a large spatial area.

KEY FINDINGS

OBJECTIVE 1

- Significant progress has been made by the research team toward development and refinement of data collection methods and standards (Figure 1). The graduate student funded through this HTIRC funding, Zach Miller, has successfully completed and defended his master's thesis on the topic. Out of this thesis, Zach and a group of co-authors have successfully published in the Journal of Forestry, and the thesis will soon be submitted to a special topic issue in the journal Drones with a focus on using UAS in forest protection.
- Despite COVID-19 challenges, Zach Miller was able to work with another graduate student in the summer and fall of 2021 to transfer research methods and results information for a smooth transition. Cameron Wingren has now taken on the research project and will expand on what Zach Miller accomplished. Cameron will focus more on the temporal recovery component and explore data collection with LiDAR on the UAS.
- Flights over controlled burn disturbances on Purdue properties were also performed during the spring and summer of 2020 and 2021 (Figure 1). This was done mainly to establish data collection workflows and to determine data processing times over a landscape known not to present difficulties in data processing and for proximity to Purdue University. Flights performed at sites containing woodlots of varying canopy structure and harvest type presented a variety of difficulties and issues which led to adjustments in determining ideal altitude and flight path overlap. During this time, it was determined that mature, dense canopy forests do present some issues, but methods are being refined to fly these at higher altitudes. Some sites also presented difficulties regarding access, airspace restrictions, and ground-based flight hazards such as power lines. Sites listed as attempted are those sites that presented issues for continued mapping.

OBJECTIVE 2

- Zach Miller was able to streamline processing and classification methods over a Purdue Wildlife Area burn disturbance site, and the Volz timber harvest site. Both sites were chosen due to the quality of the imagery gathered and processed. Although many harvest sites were flown, issues with the forest canopy prevented quality processing of this data and resulted in an incomplete orthomosaic. The Volz 125 site as seen in Figure 2 is one of three timber harvest study sites that will have more flights conducted for further classification analysis. The plan for Zach Miller is to first work on classification of the PWA and Volz timber harvest site, then expand to the other sites after establishment of a detailed workflow for an upcoming graduate student to expand the number of timber harvest types and canopy types as the research continues.
- Despite these setbacks, Joseph Hupy and Zach Miller were able to work with senior personnel member Jarred Brook over the summer on some ground truthing in the controlled burn plots. While ground truthing would have been more ideal in the timber harvest sites, a great deal of groundwork was established in terms of how to gather the ground-truthed information via ESRI Arc Collector on a mobile device.

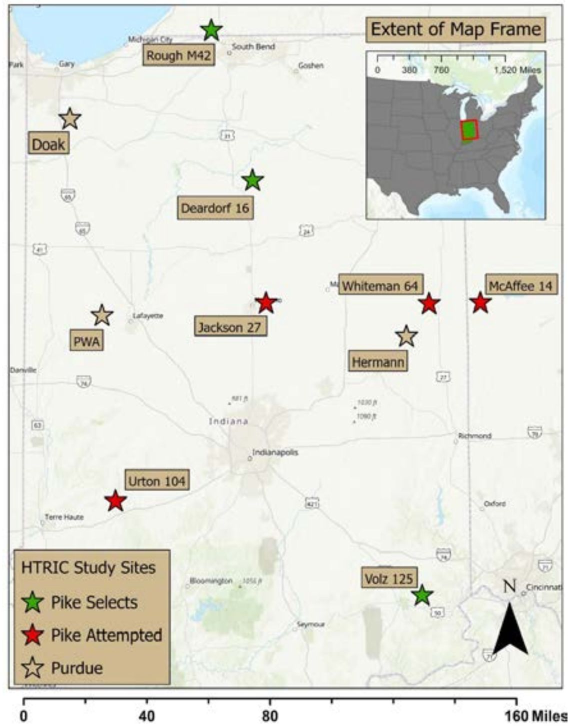


Figure 1: Locations and site name where UAS flights were conducted over the spring and summer of 2020 and 2021.

Figure 2. High-Resolution RGB Orthomosaic of the Volz 125 forest plot before (a), during (b), immediate post-harvest (c) and 30 days after harvest (d) events.

OBJECTIVE 3

- Immediately after receiving notification of funding in early 2020, Joseph Hupy worked with his graduate student Zach Miller on connecting with stakeholders to identify timber stands that reflected diverse canopy structure and timber harvest methods. Zach Miller reached out to multiple stakeholders, mainly those in charge of state forest lands and timber companies involved with managing a variety of private timber plots.
- Zach Miller worked with Pike Lumber over the spring and summer of 2020 and 2021. He was informed of timber plots that were going to be harvested, the type of harvest to occur, and a projected timber harvest date, which allowed capture of a wide variety of timber plots before a harvest event. Some of those plots have not yet been harvested, but the relationship and communications allow for Zach to be notified when those plots will be harvested in the upcoming months.
- Relationships with Pike Lumber and other stakeholders allowed for flights to be conducted over 10 different disturbance plots. Eight of those plots were forms of timber harvest disturbance, and two others were related to controlled burn disturbance (Figure 2.) Communication will continue with the stakeholders to discuss which sites will have follow-up flights occur, and to possibly include new sites that contain harvest methods or timber of noted interest.
- Cameron Wingren has continued communications with stakeholders and will conduct more flights over the next year in areas that were flown by Zach Miller. He also plans to expand into some other harvest sites that have been noted by Pike Lumber.

FUTURE PLANS

The primary issue faced by the research team was the timing of the "shelter in place" order during the early stages of COVID-19. This timing of this order came about in the early spring as planning was in place to hire undergraduate field assistants to aid in ground truthing. Despite this unforeseen hindrance, the amount of planning already done, and the fact that the work was being done within the state, allowed for a great deal of data collection to occur. The pandemic situation does continue to present challenges, however, by limiting the amount of contact between research team members and the ability to present at conferences and meetings. The research team remains hopeful that conditions will improve and allow undergraduate researchers more engagement in 2021.

Another issue encountered was the quality of data over some of the mature deciduous forest mixed canopies, despite flying at the 400-foot maximum altitude allowed by the FAA. The density of the canopy presented challenges with being able to process the data to generate the required orthomosaic for classification purposes. The issue was discussed with graduate student Zach Miller, and it was determined that because the trees presented themselves as a 100-foot ground obstacle, flights could legally be conducted at altitudes of 500 feet. A refinement in methods and approaches by flying at higher altitudes with more overlap has presented itself to resolve this issue.

- Cameron Wingren will continue to engage in data collection for the sites established by Zach Miller during the past 2 years. In addition, Cameron will examine how the planned disturbances over both the burned and harvested area have responded to the events, mainly through repeated flights over the same area.
- More work will be done regarding data collection strategies by gathering data over these areas using LiDAR and comparing this technology to the photogrammetric methods in terms of efficiency and cost.
- Publications and experience gained in this study will be utilized to apply for funding in the context of larger research projects that relate to planned disturbance events.

PARTNERS/COLLABORATORS

- Joey Gallion, *Forest Inventory Program Manager, Indiana DNR*

USING REMOTE SENSING TO CHARACTERIZE STRESS EPIDEMIOLOGY IN HARDWOOD FOREST STANDS

INVESTIGATOR(S)

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

PROJECT 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:

- Tracking insect pest and pathogen incidence, severity, and spread.
- Early detection of drought stress-related symptoms.
- Optimize RS acquisitions to determine the number of collections appropriate to make an informed management decision.

ABSTRACT

Managed forest systems contribute substantially to local, national, and global economies. Pests and pathogens have the largest negative impact on forest growth and productivity. To date, previous postdoc Ali Masjedi and current postdoc Behrokh Nazeri have coordinated manned aircraft flights over the Indiana location. Unfortunately, COVID-19 restrictions stopped travel to MO during 2020 and 2021, but plans were being adjusted to meet the stated goals of this proposal. We found that remotely sensed hyperspectral data can discriminate American chestnut (Castanea dentate) trees infected with chestnut blight (Cryphonectria parasitica) from non-diseased trees with ~80% accuracy. As severity class of disease is expanded, meaning more classes are included, then accuracy declines and disease classes become confused with one another. Research and outcomes from this work were featured in the Purdue Digital Phenomics Advisory Board, the Purdue Digital Ag seminar series, the NSF CAFS updates, and have received social media attention. Concepts from this grant have resulted in a successfully funded USDA Tactical Sciences for Agriculture Biosecurity grant (pending on approval of FY 2022 USDA budget) in 2021 with a focus on tracking invasive species.

APPROACH

- Collected and processed two years (2018-2019) of UAV hyperspectral and LiDAR data over a mixed species plot at Martell research forest that includes American chestnut with variable levels of chestnut blight to 1) identify blight stress using spectral data and 2) track blight spread through time.
- Collected two years (2019-2020) of hyperspectral data from a manned aircraft.
- Collected leaf samples (2019-2020) for stress-level chemical analyses and scored leaf blight (2018-2020).

KEY FINDINGS/ACCOMPLISHMENTS

- UAV-based spectral data can discriminate American chestnut trees with and without blight (Fig. 1). The ability of spectral data to classify blight, however, declines as additional classes of blight (e.g., none, mild, severe) are classified (Figs. 2, 3) and classes become confused with each other (Fig. 4).
- Spectral bands that are important for classification shift depending on collection period (Fig. 5).
- Work was highlighted in a 2020 Purdue Phenomics Advisory Board meeting, and a video describing work on this project has received social media attention. https://youtu.be/OWN4rF4KHJo

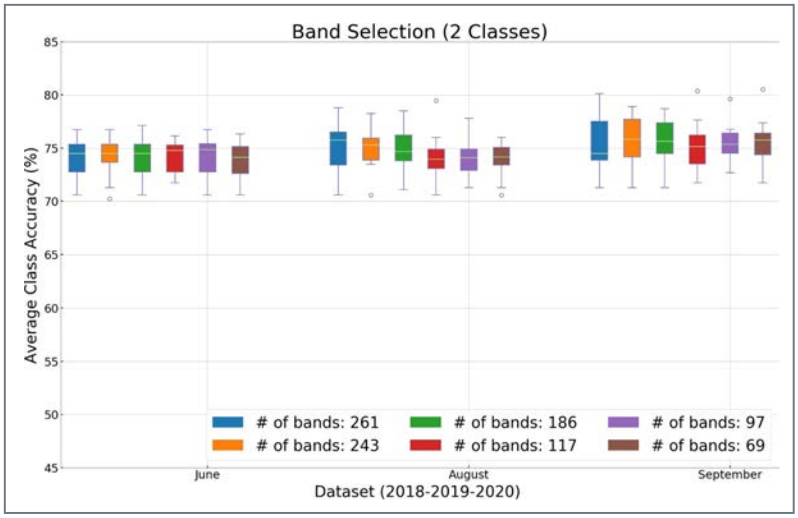


Figure 1. Classification accuracy of two-class (presence or absence) classification of chestnut blight in American chestnut trees using different spectral regions (visible and near infrared [VNIR]; shortwave infrared [SWIR]; and combined VNIR and SWIR). Classifications were made using support vector machine (SVM) algorithms.

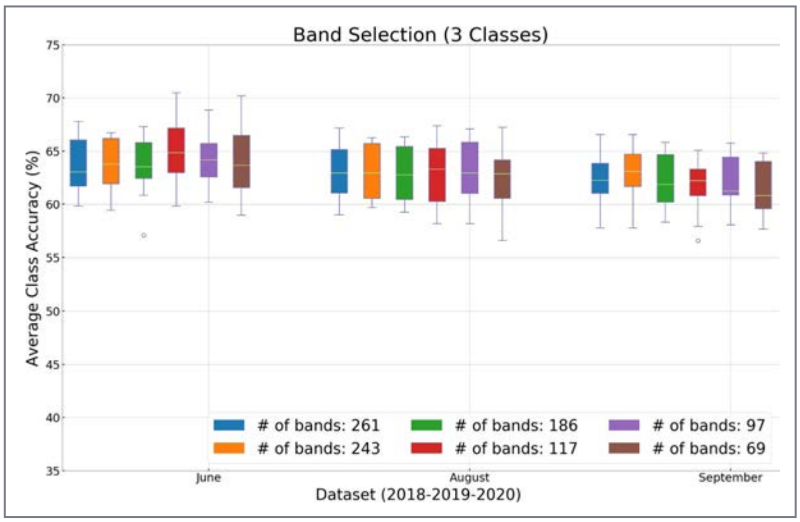


Figure 2. Classification accuracy of three-class (none, mild, or severe) classification of chestnut blight in American chestnut trees using different spectral regions (visible and near infrared [VNIR]; shortwave infrared [SWIR]; and combined VNIR and SWIR). Classifications were made using support vector machine (SVM) algorithms.

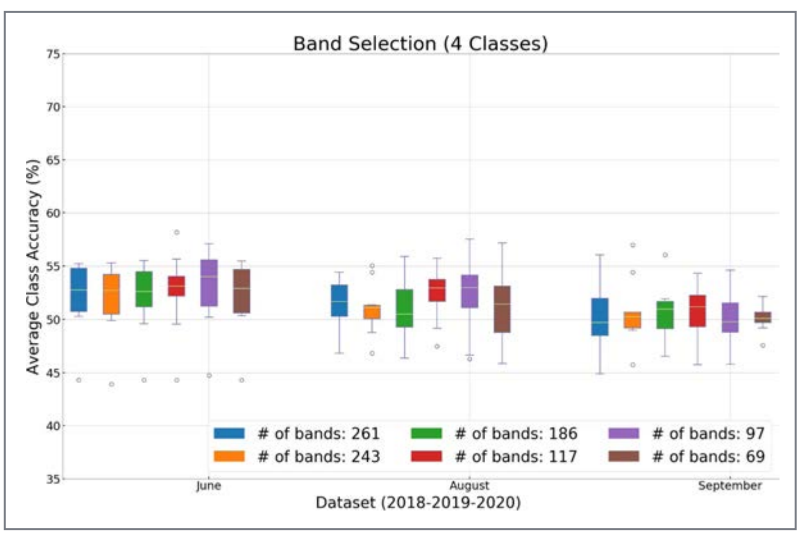


Figure 3. Classification accuracy of four-class (none, mild, moderate, or severe) classification of chestnut blight in American chestnut trees using different spectral regions (visible and near infrared [VNIR]; shortwave infrared [SWIR]; and combined VNIR and SWIR).

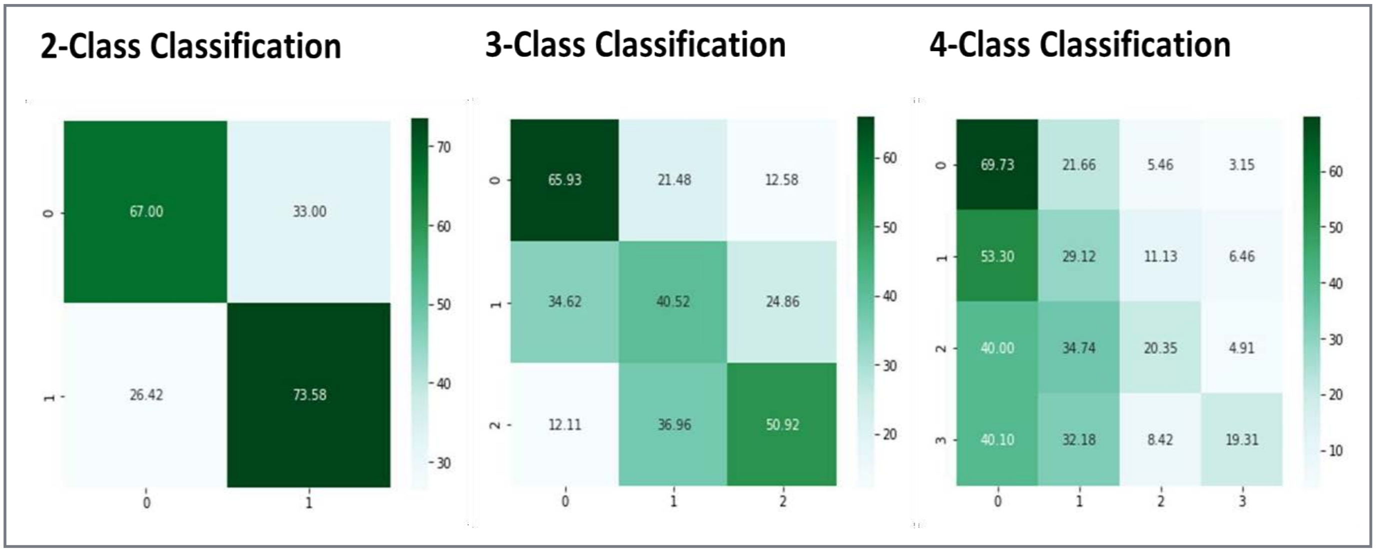


Figure 4. Confusion matrix based on classification. For example, in the far-left panel, a 0 (no blight) is accurately classified 67% of the time and misclassified as having blight 33% of the time. Notice that as classes are added more classes are confused.

FUTURE PLANS

- All spectral data were processed, except for 2021 manned aircraft collections. We will process those data when received.
- Process remaining 2020 leaf samples for chemical stress signatures.
- Score leaf blight for 2021 spectral collections.

PARTNERS/COLLABORATORS

- University of Wisconsin-Madison

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

INVESTIGATOR(S)

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

PROJECT 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.

ABSTRACT

HTIRC needs to acquire data from its many (more than 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.

APPROACH

- The research team currently includes four research advisors: Guofan Shao, Keith Woeste, Yung-Hsiang Lu, and James Warren. Thirteen undergraduates and one graduate student: Jessica Budde, Collin Campbell, Nick Eliopoulos, Yiting Gan, Aaryan Garg, Yi-Fang Hsiung, Dainong Hu, Yunmei Huang (graduate), Zren Li, Sohan Pramanik, Abhiram Saridena, Yezhi Shen, Rohit Tokala, and Hoang Tran.
- The students are divided into four topic areas – tree segmentation and classification (Nick, Aaryan, Rohit), stem straightness and volume computation (Yiting, Dainong, Sohan, Aaryan), tree image recognition and matching (Yi-Fang, Hoang, Zeren, Yezhi), tree-bark-based species recognition (Collin, Yunmei), and new sensor testing (Jessica for Lidar, Abhiram for Oak-D).
- The team met twice a week for an entire year. Each student gave a report or feedback on research they have been working on every week (Fig. 1).
- The team bought a notebook computer and an Oak-D camera.
- The project fund (budget) was used to pay four of the most advanced students on an hourly basis.

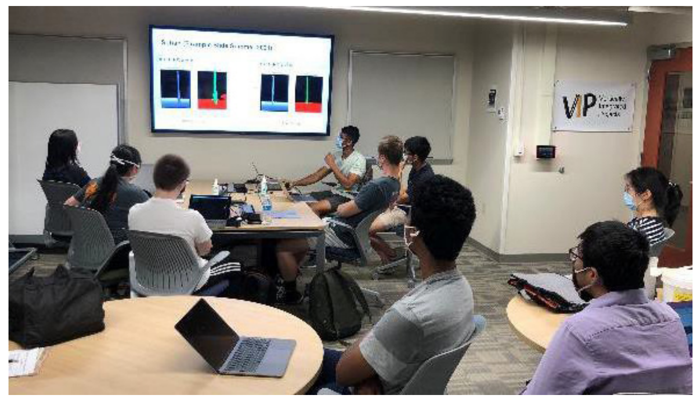


Figure 1. A weekly meeting of the research team in fall 2021.

KEY FINDINGS

The team has further improved real-time measurements of tree attributes. Depending on camera resolutions, the RMSE of DBH computations range from 1.22 cm to 2.27 cm (Fig. 2). This indicates that higher DBH accuracy can be achieved with a higher resolution camera. The accuracy can be improved further if an apparent systematic underestimation of DBH is corrected, a problem under investigation. Our goal is to reach steady 0.5 cm or less DBH error. Error of this magnitude is lower than what is achievable using hand measurement.

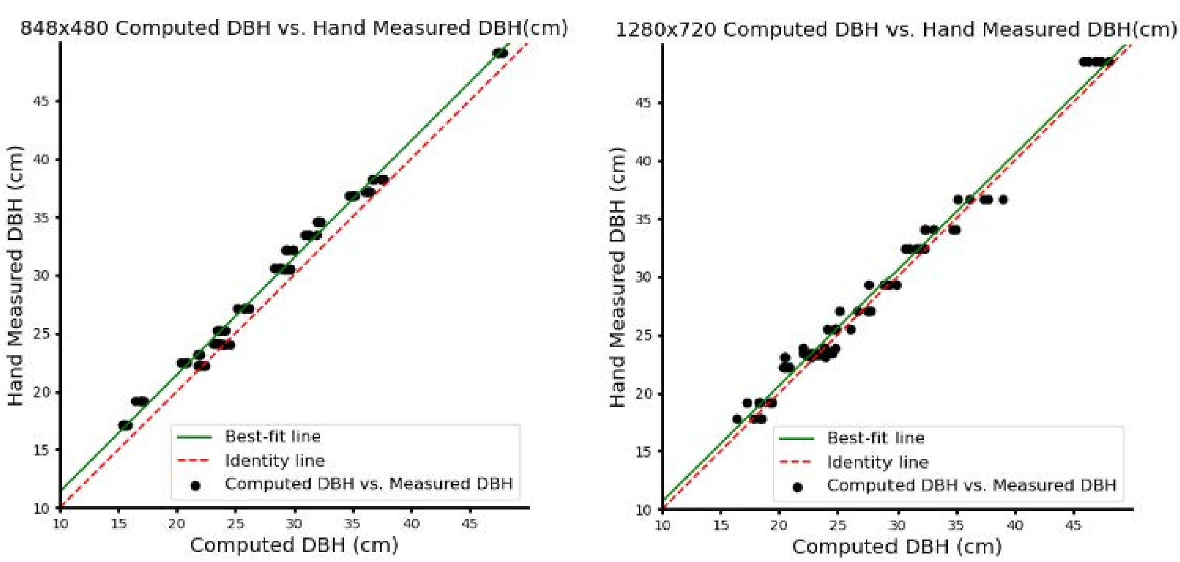


Figure 2. Comparisons of field DBH measurements and computed DBH values.

The team has made breakthroughs on tree segmentation and classification using neural networks (NN). Segmentation refers to the assignment of objects or features into their proper category, e.g., stem, ground, branch, or background. Software developed by the team uses computer vision technology to determine first branch height and the trunk-ground intersection (Fig. 3). The detection accuracy reached 91%. Our team's software uses a properly segmented image to measure diameter at any height along a tree stem. The goal of this research is to obtain a correct detection of lowest branch 95% of the time. NN based detection of the lowest branch, and the trunk/ground intersection determines the portion of the tree that is commercially useful and is essential for calculating traits such as log volume.

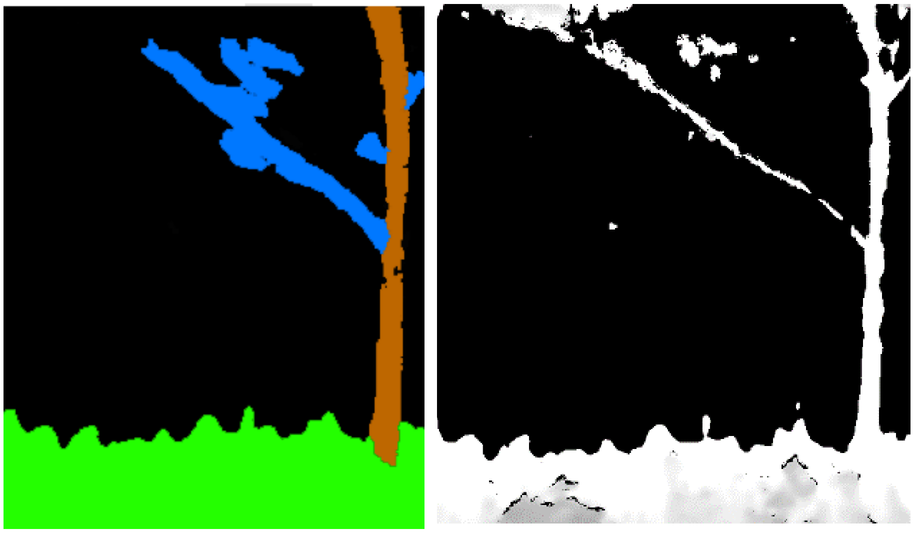


Figure 3. Tree segmentation and classification (left) based on depth imagery (right).

The team developed a computer interface for automated tree recognition and matching between consecutive measurements over time (Fig. 4). This progress makes it possible to automatically update an existing database in real time (as measurements are being taken). This feature saves time and ensures the consistency of periodic tree measurements.

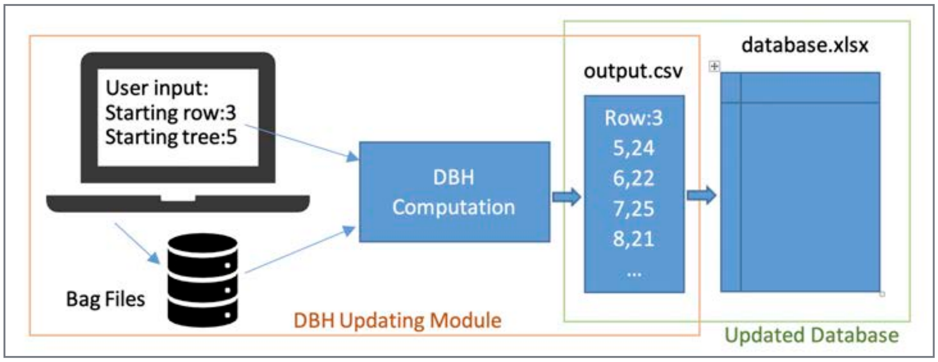


Figure 4. Illustration of automated tree ID patching and database updating.

FUTURE PLANS

- The team has collected data necessary to write manuscripts related to the three research areas above.
- An algorithm for the automated, quantitative measurement of tree straightness is under development.
- The team has also started preparing documentation for intellectual property disclosure and patent application.

PARTNERS/COLLABORATORS

- James Warren, Biological Scientist/Operational Tree Breeder, USDA Forest Service
- Joey Gallion, Forest Inventory Program Manager, Indiana DNR

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

INVESTIGATOR(S)

- **Rado Gazo**, *Professor, Forestry and Natural Resources, Purdue University (gazo@purdue.edu)*
- **Bedrich Benes**, *Professor, Computer Graphics and Computer Science, Purdue University*
- **Songlin Fei**, *Professor, Forestry and Natural Resources, Purdue University*

OBJECTIVES

This project has three objectives. We are in the second year, during which we proposed to fulfill objective #1 and start working toward objective #2.

Objective #1 – This objective focuses on evaluating the existing image acquisition hardware at a cooperating sawmill, determining whether a hardware upgrade is needed, and performing such an upgrade. We have collected images with existing hardware but determined that working toward this objective is premature. We must fulfill objective #2 before we can address #1. The same is true about objective #3.

Objective #2 – All of our work in Year 2 was focused on this objective, and we achieved significant progress. This objective focuses on developing an image pre-processing method to remove artifacts such as saw marks and other noise, and on developing novel image analysis techniques to calculate log cross-section maximum, minimum and average diameter, detect pith and geometric center of the cross section, calculate tree age and growth rate using the growth ring analysis and potentially other biometric data.

APPROACH AND KEY FINDINGS

Dendrochronology (tree-ring dating) is a quantitative dating method based on analyzing information from the growth ring of trees. Tree-ring dating is not only beneficial for scientific purposes but essential in the wood industry. Basic image processing techniques have been applied to automatic detection of tree-ring boundaries and consequently help in tree ring measurement. But performance of such approaches is limited, especially when the wood surface is rough. In this project, we focus on providing a better dataset for the research of automatic detection of tree-ring boundaries as well as developing deep learning-based models to solve the problem. We are using deep learning image segmentation methods to address this issue.

First, we established the image-processing pipeline that consists of: 1) Edge image processing, 2) Finding pith and radius, 3) Detecting chain saw marks direction, and 4) Processing growth plot. We also developed software and user interface to assist in image analysis. A manuscript describing our initial pipeline establishment, "Convoluted Neural Network training, accuracy results and limitations," is currently under review.

Second, we developed a database of images collected with various cameras and under various conditions (rough, smooth, smooth finished) of two sides of 136 tree cookies for 11 common central Midwest hardwood species as outlined below.

Table 1. Common Midwest hardwood tree species and number of tree cookies used to develop an image database.

Species	Common name	Cookies #
Fraxinus spp.	Ash	11
Tilia americana	Basswood	11
Juglans nigra	Black walnut	14
Prunus serotina	Cherry	13
Celtis occidentalis	Hackberry	10
Acer saccharum	Hard maple	14
Carya spp.	Hickory	12
Quercus rubra	Red oak	14
Acer saccharinum	Soft maple	12
Quercus spp.	White oak	14
Liriodendron tulipifera	Yellow poplar	11
Total		**136**

Third, we annotated one slice per each cookie (width = 128 pixel) and each ring edge by manually marking 3 points.

Fourth, we developed an image segmentation-based method to identify rings when the surface is clean. Partial results of algorithm performance are in the table below.

Table 2. Partial results of algorithm performance for image segmentation-based method to identify tree rings on a clean surface.

Surface	TP	FN	FP	SEN	PREC	F1
Rough	1450	863	1563	0.63	0.48	0.54
Clean Dry	1508	550	1072	0.73	0.58	0.65
Clean Wet	1891	273	876	0.87	0.68	0.77

Overall, for most species, the F1 scores range from 0.7 to 0.9, showing that the model could discover ring edges. However, for some species, e.g., white oak and hard maple, the F1 scores are low, indicating the potential failure of the models. Since we trained only one model for all species, that failure might come from the anatomy structure. White oak and hard maple are with abundant and banded parenchyma cells. Those features might make the model detect more false ring edge boundaries.

Table 3. Results of image segmentation-based method to identify tree rings with common Midwest hardwood tree species.

Species	Common name	TP	FN	FP	REC	PREC	F1
Fraxinus spp.	Ash	126	6	118	0.95	0.52	0.67
Tilia americana	Basswood	207	32	76	0.87	0.73	0.79
Juglans nigra	Black walnut	251	16	68	0.94	0.79	0.86
Prunus serotina	Cherry	201	26	107	0.89	0.65	0.75
Celtis occidentalis	Hackberry	68	9	18	0.88	0.79	0.83
Acer saccharum	Hard maple	36	6	36	0.86	0.50	0.63
Carya spp.	Hickory	169	18	15	0.90	0.92	0.91
Quercus rubra	Red oak	276	30	126	0.90	0.69	0.78
Acer saccharinum	Soft maple	326	98	89	0.77	0.79	0.78
Quercus spp.	White oak	149	21	145	0.88	0.51	0.64
Liriodendron tulipifera	Yellow poplar	82	11	78	0.88	0.51	0.65

FUTURE PLANS

To increase performance of ring detection when the surface is rough and dirty, the full cookie area should be annotated and considered due to the poor performance when applying the current method. We will also consider improving the current algorithm to increase the accuracy.

2021 HTIRC-FUNDED RESEARCH GRANTS

BACKPACK SYSTEM FOR HIGH-RESOLUTION FOREST INVENTORY

INVESTIGATOR(S)

- **Ayman Habib**, *Professor, Civil Engineering, Purdue University, (ahabib@purdue.edu)*
- **Songlin Fei**, *Professor, Forestry and Natural Resources, Purdue University*

PROJECT OBJECTIVES/APPROACH AND FINDINGS

Objective 1. Optimize system integration, data logging, and deployment of Backpack LiDAR system

To date, the research team has developed three backpack LiDAR systems.

- First system is equipped with a Sony 7RII digital camera, NovAtel SPAN-CPT position and orientation system, and Velodyne VLP-16 Hi-Res LiDAR unit (Figure 1 – left)
- Second system is equipped with an Ouster OS0 32 LiDAR unit and NovAtel PwrPak E1 position and orientation system (Figure 1 – middle)
- Third system is equipped with a Velodyne VLP-16 LiDAR unit and NovAtel PwrPak E2 position and orientation system (Figure 1 – right)

For the different backpack systems, data acquisition protocols and user manuals have been established.

The backpack systems have been used for several data acquisition campaigns at Martell Forest for both plantation and natural plots under leaf-off and leaf-on conditions. In addition to the deployment of the backpack LiDAR, UAV LiDAR missions have been conducted.

Figure 1. Prototypes for the three different backpack systems equipped with VLP 16 High-Res (left), Ouster (middle), and VLP 16 (right) LiDAR units.

Objective 2. Develop data processing and biometrics extraction algorithms

For this objective, the research team has been focusing on two major tasks:

- Develop strategies for trajectory enhancement to mitigate GNSS signal outages while collecting data under forest canopy – In this task, terrain patches and individual tree trunks have been extracted from individual backpack tracks and used for adjusting the GNSS/INS-based trajectory. Such adjustment has reduced the inter-track misalignment from more than 2 m to less than 5cm (Figure 2). At this stage, the used procedure has been implemented for forest plantations. Now, we are working on expanding this strategy to handle natural forests.

- Develop data analytics strategies for forest biometric extraction – The team has been working on developing strategies for ground/non-ground filtering of acquired point clouds. Aboveground point clouds are then used for the individual tree detection and localization, tree height estimation, and DBH evaluation. Current approaches are mainly targeting plantations. The developed strategies will be expanded to natural forests.

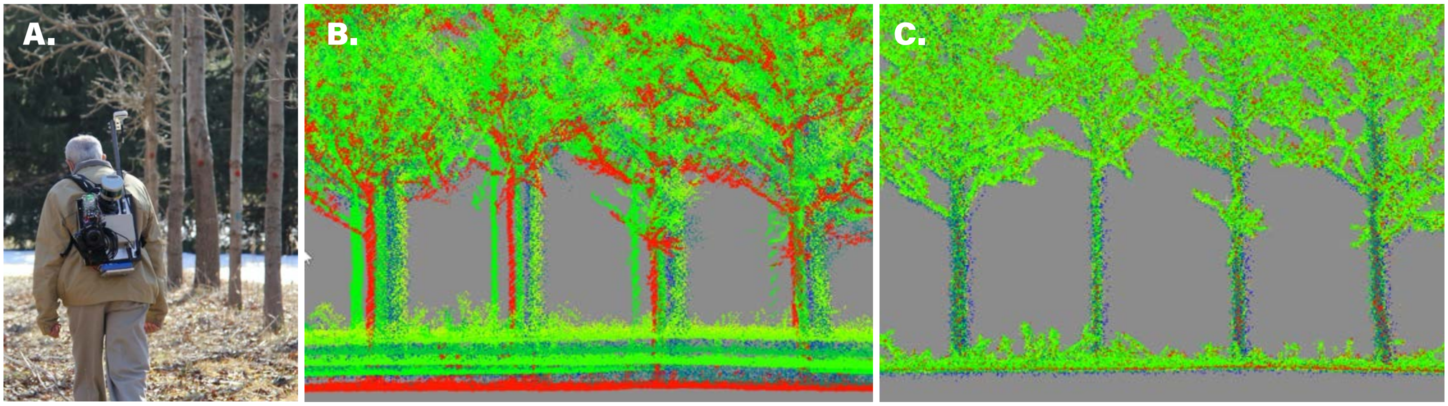


Figure 2. Backpack deployment in Martell Forest (a), and LiDAR point clouds before (b) and after (c) trajectory enhancement.

Objective 3. Share tools and methods with HTIRC researchers and stakeholders in trainings and workshops.

The project team has been active in the dissemination of preliminary results in the form of posters, presentations, and communications to other stakeholders within and outside Purdue (e.g., HTIRC annual meeting – Figure 3, Morton Arboretum, Indiana Hardwood Lumbermen's Association). Moreover, we have one journal paper that has been published (Lin et al., 2021). Two other publications are finalized – one is submitted for publication at the ISPRS Journal for Photogrammetry and Remote Sensing and the other one will be submitted for peer review to the Remote Sensing Journal. For scalable implementation of the developed backpack systems and data processing strategies, the team has been collaborating with VeriDaas Corporation (https://veridaas.com/), which has a Giger Mode LiDAR that can provide point cloud data for larger areas at a lower cost due to its ability to collect high-resolution data from higher altitude while flying at a faster speed. VeriDaas has provided high-resolution point cloud for Martell forest in September (leaf-on) – Figure 4. Another dataset was acquired in early December 2021 (leaf-off) and has been available to the research team since early January 2022.

Figure 3. Demonstration of the Backpack LiDAR System at the HTIRC Annual Meeting on October 15, 2021.

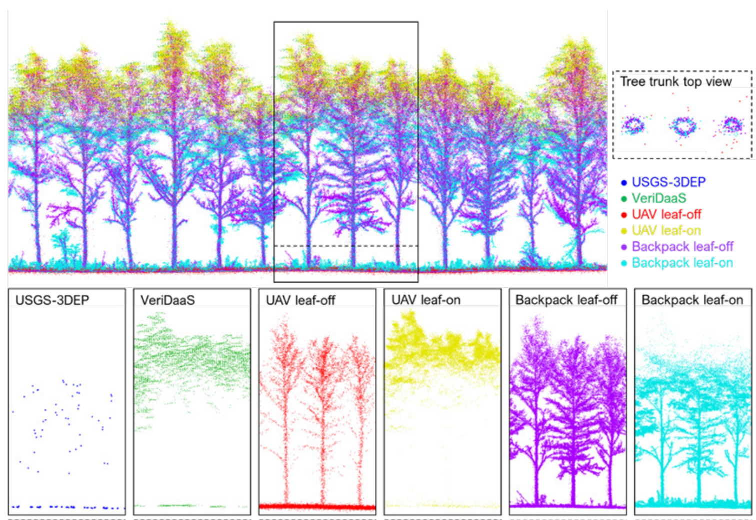


Figure 4. Cross-sectional profile of point clouds over Martell forest from the statewide, VeriDaas Giger mode, UAV, and Backpack LiDAR systems.

PARTNERS/COLLABORATORS

- Guofan Shao, *Professor, Forestry and Natural Resources, Purdue University*
- Joey Gallion, *Forest Inventory Program Manager, Indiana DNR*

TESTING EFFICACY OF UNDERPLANTING AND ENRICHMENT PLANTINGS FOR STAND REGENERATION IN HARDWOOD FORESTS

INVESTIGATOR(S)

- **Douglass F. Jacobs**, *Fred M. van Eck Professor, Forestry and Natural Resources, Purdue University (djacobs@purdue.edu)*
- **Don Carlson**, *Forester, Forestry and Natural Resources, Purdue University*
- **Ron Rathfon**, *Extension Forester, Forestry and Natural Resources, Purdue University*
- **Caleb Redick**, *Research Associate, Forestry and Natural Resources, Purdue University*
- **Michael Saunders**, *Associate Professor, Forestry and Natural Resources, Purdue University*

PROJECT OBJECTIVES

- Revisit and assess long-term (> 10 years) performance of hardwood underplantings and enrichment plantings across the full network of available FNR trials and attempt to link success or failure to site conditions, silvicultural treatments at establishment, and/or subsequent management regimes.
- Evaluate hardwood tree responses to competition release for a subset of trials in Objective 1 that are at the appropriate developmental stage and have sufficient stocking of dominant or co-dominant trees.
- Establish and maintain a network of demonstration trials to be used as a resource for HTIRC / Purdue FNR Extension field days to communicate results of these long-term trials to landowners and foresters.

ABSTRACT

Oaks (Quercus spp.) and other valuable hardwood species provide important economic, ecological, and wildlife values, but regeneration failures in natural forests are common. Underplanting and enrichment plantings may provide an alternative means to increase the abundance and diversity of advance reproduction of desirable hardwoods in the forest understory. Most of these studies have been short-term, however, with relatively few extending beyond 10 years. Thus, a more comprehensive knowledge of the longer-term responses of underplanting and enrichment plantings is needed. We are taking advantage of a network of existing HTIRC / Purdue FNR underplanting and enrichment planting demonstration trials and research experiments established over the past 20 years in natural forest stands on FNR woodlands throughout Indiana. We are assessing long-term performance of underplanting and enrichment plantings across this network of sites. Using this data and an assessment of site conditions, we will develop models to best explain relative long-term success or failure of these plantings. We will use a subset of trials from those in Objective 1 that are at the appropriate developmental stage and have sufficient stocking of future crop trees to examine responses to release from competition. Then we will establish and maintain these sites as a network of demonstration trials to be used as a resource for HTIRC / Purdue FNR Extension field days to communicate results of these long-term trials to landowners and foresters. Our project will enhance knowledge of the long-term responses of these plantings specific to the relatively mesic site conditions characterizing Indiana and the surrounding region. Through our Extension and outreach efforts, we will ensure that these results are extended to forest managers and HTIRC stakeholders to help develop effective prescriptions for hardwood underplantings and enrichment plantings.

APPROACH

ASSESS LONG-TERM PERFORMANCE OF UNDERPLANTING AND ENRICHMENT PLANTINGS

- Revisit each of the planting demonstration trials and research experiments (Table 1, Figure 1) to assess long-term performance.
- On each of the sites, we are identifying and recording the number of planted trees by species, and measuring their height, diameter (DBH), and competitive status (dominant/co-dominant, intermediate, or suppressed). These data will be compared to the original planting records to determine survival, growth, and vigor or planted trees by species.
- Simultaneously, we will assess competing tree species on each of the sites, including seeded volunteers and stump sprouts.
- Using this newly recorded data and a full assessment of site conditions (e.g., site quality, soil types, silvicultural harvest treatments, intermediate vegetation management), we will develop models (e.g., Figure 2) that best explain relative long-term success or failure of underplanting and enrichment plantings.

EVALUATE CROP TREE RESPONSES TO RELEASE TREATMENTS

- We will identify a subset of trials that are at the appropriate developmental stage (i.e., ca. 10 years old) and have sufficient stocking of dominant or co-dominant future crop trees to examine response to release from competition.
- To accomplish the release treatments, we will use a split-plot design where half of the replicate plot is randomly allocated to receive release or else designated as a control (no release). Release treatments will consist of a full (4-sided) crown release, which is appropriate for this developmental stage. Trees that are not in a competitive (dominant and co-dominant) position will be excluded, because they are unlikely to respond.
- In addition to release of our planted trees, we will identify natural regeneration (stump sprouts, seeded trees) of desirable species (e.g., oaks) in a similar age class and competitive position in all plots and release these trees in the split plots designated for release, which will further allow for comparison of responses to release for planted trees vs. natural regeneration.
- To quantify response to release, all experimental trees will be measured for height and DBH, as well as canopy volume (as a function of crown height and crown diameter) at time of release and after each of the next two growing seasons.

Table 1. The network of existing HTIRC / Purdue FNR underplanting and enrichment planting trials established over the past 20 years in natural forest stands on FNR woodlands.

Year	Location	Species	Treatments	Notes
2001	Nelson-Stokes	red oak	container vs. bareroot	two openings; post windstorm; some release treatment.
2003	SIPAC	red oak	container vs. bareroot, gap size	Morrissey et al. 2010; ~20% of planted oak were deemed competitive at 5 years.
2006	Harrold	red oak, white oak, walnut, cherry	half fenced, genetically select vs. not	1 replicate – demonstration.
2008	Stephens Darlington	red oak	container vs. bareroot, simulated browse	Woolery and Jacobs 2014
2010	Nelson-Stokes	red oak, white oak	half fenced, canopy removal	Frank et al. 2018; overstory thinning, mid-story removal, combo (shelterwood), control. Additional replicates available on TNC properties.
2011	Nelson-Stokes	red oak, white oak	gap study	Four years of weed control, fenced, no release but most trees free-to-grow.
2013	SEPAC	red oak, white oak, chinquapin oak, chestnut	half fenced, four management levels	Underplantings in clearcut. 25% no management, 75% treated year 1, 50% second year weed control. 25% still needs release.
2013	SEPAC	red oak, white oak, swamp chestnut oak	half fenced, browse control	Underplantings in clearcut. Tree tubes, Repellex in nursery and/or field, spray repellent, untreated control.

Figure 1. Example of large container red oak shortly after planting into the largest (~1-acre) harvest gap treatment at SIPAC in 2003 (left). Planted red oaks and natural regeneration in the largest harvest gap size treatment at SIPAC in 2006 after four growing seasons (right).

FINDINGS

- At Nelson-Stokes, northern red oaks after 20 years had 41% survival, an average diameter of 51 mm, average height of 669 cm, and 21% of survivors had a crown class intermediate or above.
- At Block C1 at the SEPAC Biomass planting, overall survival was 68% after 8 years. For northern red oaks, average diameter was 23 mm inside fences and 18 mm outside fences, and average height was 402 cm inside fences and 327 cm outside fences; 53% of survivors had a crown class intermediate or above inside the fence, and 43% of survivors had a crown class of intermediate or above outside the fence. For white oaks, average diameter was 20 mm inside fences and 16 mm outside fences, and average height was 324 cm inside fences and 265 cm outside fences; 42% of survivors had a crown class intermediate or above inside the fence, and 32% of survivors had a crown class of intermediate or above outside the fence. For chestnuts, average diameter was 53 mm inside fences and 51 mm outside fences, and average height was 605 cm inside fences and 574 cm outside fences; 100% of survivors had a crown class intermediate or above inside the fence, and 77% of survivors had a crown class of intermediate or above outside the fence. For chinkapin oaks, average diameter was 22 mm inside fences and 21 mm outside fences, and average height was 414 cm inside fences and 382 cm outside fences; 52% of survivors had a crown class intermediate or above inside the fence, and 33% of survivors had a crown class of intermediate or above outside the fence.

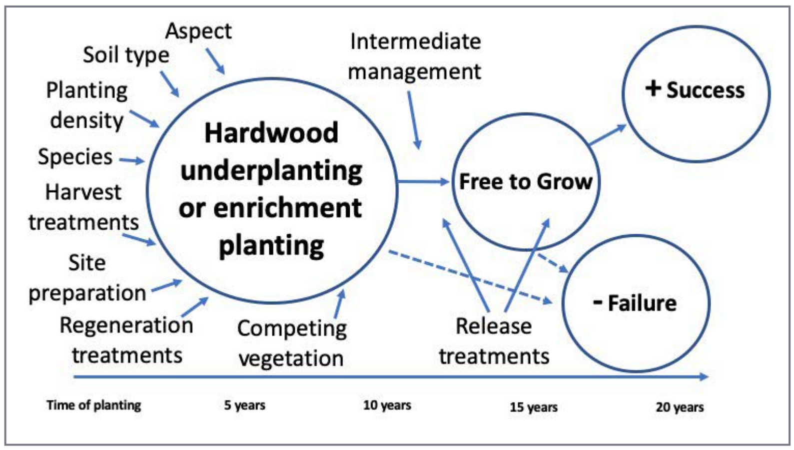


Figure 2. Example of factors that may help to explain relative success of underplanting and enrichment plantings.

FUTURE PLANS

- Finish identification and measurement of trees
- Perform release treatments and follow-up
- Hold an Extension field day highlighting this project in 2022 and again in 2023
- Update FNR-225 (Enrichment planting of oaks, by Morrissey et al. 2007) with our project results

BETTER BLACK WALNUT BY BREEDING WITHOUT BREEDING

INVESTIGATOR(S)

- **Keith Woeste**, *Molecular Geneticist and Project Leader, USDA Forest Service, Adjunct Assistant Professor, Forestry and Natural Resources, Purdue University (keith.woeste@usda.gov)*
- **Richard Cronn**, *Research Geneticist, Pacific Northwest Research Station, Corvallis, OR*
- **Denita Hadziabdic**, *Assistant Professor, Entomology and Plant Pathology, University of Tennessee*
- **Mo Zhou**, *Assistant Professor, Forestry and Natural Resources, Purdue University*
- **James McKenna**, *Operational Tree Breeder, USDA Forest Service, retired*
- **James Warren**, *Biologist/Database specialist, USDA Forest Service*

PROJECT OBJECTIVES

- Determine a SNP genotype (DNA fingerprint) for all 242 parents in the HTIRC black walnut breeding program and for 2,750 seedlings in progeny trials, to determine their paternity, genetic diversity, and relatedness.
- Use modern statistical methods (GBLUP) to identify superior black walnut parents for height growth, diameter growth, and straightness on a range of sites, describe their benefits in an Extension publication, and make them available for propagation into the Indiana State Tree Nursery Seed Orchard and other seed orchards.

ABSTRACT

Undergraduate students were hired. Tree measurements and phenotyping, tissue collection, and DNA extraction were begun. In some cases, these steps required re-establishing contact with landowners, finding maps, and verifying the existing map based on trees remaining at the study sites. The retirement of Co-PI McKenna made these steps more difficult than we hoped, and in some cases out of date or (potentially) inaccurate maps required us to collect more data and samples than we planned to ensure the needed samples are available for analysis. After conversations with Mike Saunders, we added additional measurements for a sample of trees to improve the data we have for management of black walnut in plantations. The added measurements included canopy height, height to live crown, and crown width. So far, 384 progeny have been measured. These data benefit any future users of black walnut data from these plantations. Co-PI Hadziabdic, who oversees DNA isolation, reports 155 DNA extractions are completed from 55 samples. We are investigating methods to speed up the extraction and to have extractions performed at considerably less cost by a commercial vendor.

APPROACH

- Tree measurements are performed as in classical forestry.
- DNA-based data is obtained by genotyping DNA samples of progeny and their parents using a ~300 SNP panel developed by Co-PI Cronn.
- The SNP data will be used to assemble a matrix of relatedness among sampled plants. The relationship matrix is added to a classical (statistical) generalized linear model including seedling age, location, block, etc. The combined analysis is called GBLUP (genetic best linear unbiased prediction) and is conceptually like adding a spatial term to standard linear model, except the “space” that is accounted for is genetic relatedness.

KEY FINDINGS

- We are still in the data collection phase, but we will report several important programmatic accomplishments:
- Records related to the location and condition of several HTIRC plantations that had not been properly tracked, including new landowners and their contact information, have been updated or added to the HTIRC database.
- Maps of sampled sites have been updated.
- Data on tree size and architecture that was not part of the original study plan was collected and added for the use of other HTIRC researchers.
- Re-established contact with landowners led to increased interest in using HTIRC resources to manage their plantations going forward, creating opportunities for additional collaboration.

FUTURE PLANS

- We hope to complete a large percentage of the measurements in early 2022.
- We are determining if DNA isolation from dormant twigs will be possible. If so, we also hope to continue DNA collection in early 2022.
- SNP genotyping will begin as soon as possible.

PARTNERS/COLLABORATORS

- Evonik Corp.
- Steelcase Corp.
- Forgey Family Farm

DIGITIZATION OF HISTORICAL GENETIC AND TREE IMPROVEMENT TRIALS ACROSS THE EASTERN US

INVESTIGATOR(S)

- **Rebekah Shupe**, *Research Associate, Forestry and Natural Resources, Purdue University (rfshupe@purdue.edu)*
- **Songlin Fei**, *Professor, Forestry and Natural Resources, Purdue University*
- **Carrie Pike**, *Regeneration Specialist, USDA Forest Service, Northeastern Area State & Private Forestry, Adjunct Assistant Professor, Forestry and Natural Resources, Purdue University*

PROJECT OBJECTIVES

- Preserving historical (pre-1980) documents and data from genetic and tree improvement trials in a digital format.
- Create a public database and directory of metadata and raw data of historical genetic and tree improvement trials.
- Create figures to represent data in meaningful ways.

ABSTRACT

Throughout the mid-to-late 20th century, federal, state, and tribal governments across the US established thousands of genetic and tree improvement field trials across the U.S. These studies were established primarily for hardwood and conifer tree species with commercial value to study genetic variation within and among different populations. However, through time, many of these plantings have been abandoned or forgotten due to the retirement of key scientists, lack of funding, a shift in priority, the degradation or loss of plantings, or loss of data. Though many plantings have been lost, some plantings still exist on the landscape along with their hard copies of data residing in offices and storage facilities. This untapped resource is in demand by 21st-century scientists to help answer questions about the impact of environmental stress on native forest trees. Locating these plantings and their data is essential to help answer questions about the adaptability of our tree species to future climates.

APPROACH

- Used “A Guide to Forest Tree Collections of Known Source or Parentage” by Raymond Guries, Susanne Brown, and John Kress, “1981 Directory of Forest Tree Seed Orchards in the United States” by the USDA Forest Service, and “A Guide to Forest Genetics Field Trials at North Central Forest Experiment Station” by Jerry Van Cleve, Don Riemenschneider, and George Rink to create a list of historical genetic tree plantings.
- Verified the existence of plantings from the list by contacting affiliated scientists and using Google Earth Pro™.
- Visited Vallonia State Nursery in Vallonia, IN, the University of Missouri in Columbia, MO, USDA Forest Service Region 9 Office in Milwaukee, WI, Pennsylvania State University in State College, PA, and Cloquet Forestry Center in Cloquet, MN to digitally scan and physically collect the data of historical genetic tree plantings to digitize in an electronic format.
- Created website, database, and directory for currently verified plantings that can be accessed by interested researchers.
- Generated a workflow for producing stem maps of verified and extant plantings using Lidar images.

KEY FINDINGS

- Using the above approach, the existence of 540 plantings has been confirmed throughout 13 states. Of the 540, a total of 323 plantings were confirmed to be in existence and the remaining 217 were not recoverable.
- Out of the 540 plantings that have been confirmed, only 166 have an accompanying dataset. The data that is available for those plantings is very limited, and most of it does not include raw data.
- When compared to in-person measurements, the stem maps generated through RStudio™ using Lidar images are very accurate.
- Have digitized approximately 15% of collected data.

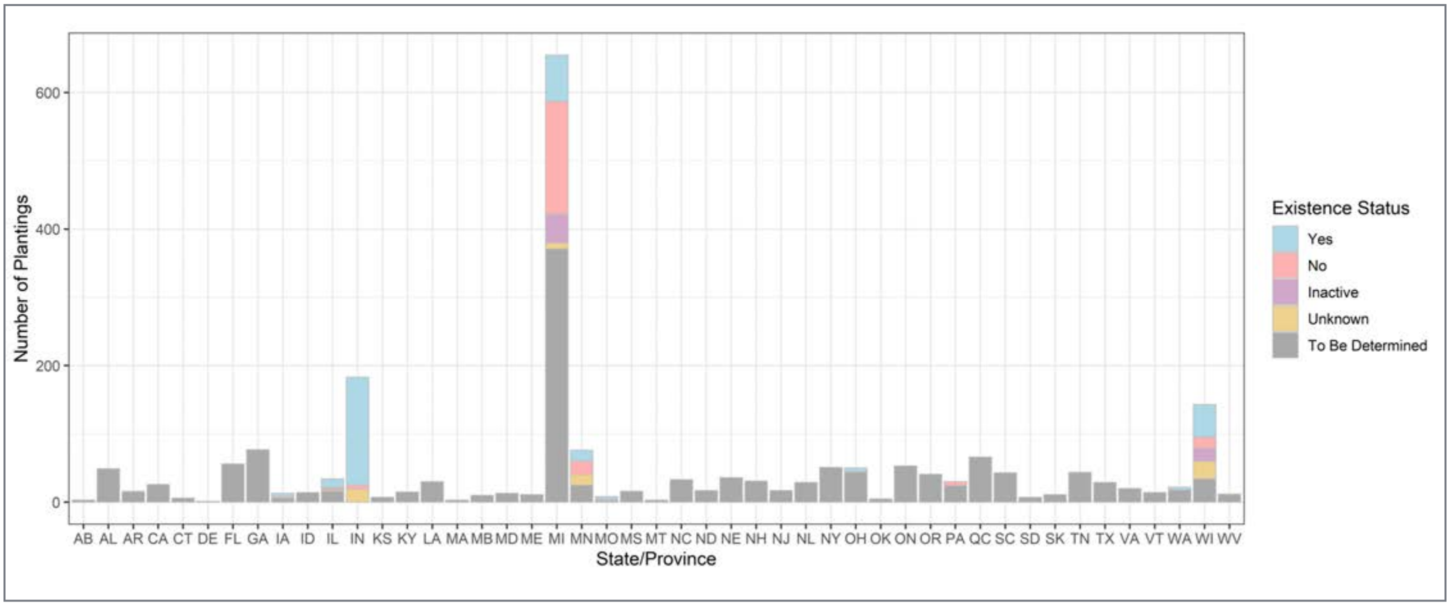


Figure 1. Genetic tree plantings across 40 U.S. states and 7 Canadian provinces and the count of genetic tree plantings still in existence (light blue); no longer in existence (light red); inactive (lilac), which is defined as plantings that were abandoned but not removed; unknown (yellow), which are plantings that cannot be located based on our information; and to be determined (gray), which are plantings that will be verified.

FUTURE PLAN

- Continue confirming the existence of genetic tree plantings in the eastern U.S.
- Mention states I will be working on next
- Finish digitizing collected data and travel to other states to scan and collect data.
- Finish digitizing data
- Create a more functional website that will provide more information on the genetic tree plantings we have confirmed, such as estimated tree survival rate, and have data files available for download.
- Write and publish a paper discussing our database and how other researchers can contribute and access it.

PARTNERS/COLLABORATORS

- USDA Forest Service

Collaborators

James Warren, Yue “Shirley” Li, Sungchan Oh, Nicholas Labonte, Paul Bloese, Ron Zalesny, Andrew David, Ed Bauer, Raymond Guries, Stuart Seaborne, Phillip O’Connor, Mark Coggeshall, Yvette Amerman, Dave Horvath, Kim Steiner, John Kabrick, Lauren Pile, Travis Swaim, and Josh Abercrombie.

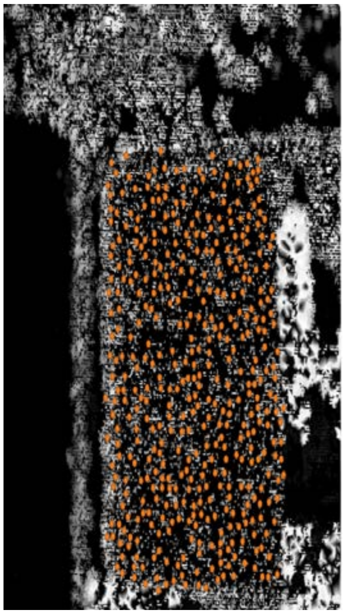


Figure 2. Stem map of a red oak (Quercus rubra) provenance trial from 1962 located at Martell forest in West Lafayette, IN.

ENGAGEMENT AND EXTENSION

The role of HTIRC outreach is to connect our partners, collaborators, and stakeholders with the people, information, and products of the HTIRC.

HTIRC NEWS

One news highlight in 2021 was the article on the Digital Forestry Initiative led by Dr. Songlin Fei, "Remote sensing, digital tech advance tools for precision forestry." (https://ag.purdue.edu/stories/remote-sensing-digital-tech-advance-tools-for-fast-precision-forestry/).

- For the latest HTIRC news, check out the following:
- Fall and spring E-newsletters (https://htirc.org/resources/newsletters/)
- News archive (https://htirc.org/news/news-archive/).
- Annual reports (https://htirc.org/annual-report/)

EXTENSION PRODUCTS

- In 2021 we produced a variety of online resources, including videos on hardwood management produced by Lenny Farlee. These are posted at https://htirc.org/resources/landowner-information/ and include:
- ID That Tree series: 53 videos were released in 2021, garnering 26,996 views
- Woodland Management Moment series: This series covers various woodland management topics, with 3,946 views in 2021.
- Woodland Stewardship for Landowners video series: 10 videos have been released from this collaborative series between Purdue FNR and the Indiana Department of Natural Resources
- The Planting and Care of Fine Hardwood Seedlings publications 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 more than 28,500 publication downloads/views in 2021.

PROGRAMS

- These programs shared the latest HTIRC information to landowners and/or natural resources professionals in a mix of online and in-person formats:
- Landowners Conservation Tree Planting Workshops
- Forest Management for the Private Woodland Owner course
- Walnut Council Field Days (3)
- Forest Pesticide Applicators Continuing Education Program
- Tree Farm/IFWOA Landowners Field Day
- Matthew Ginzel provided identification, impact, and management strategies for Thousand Cankers Disease in the SE United States as part of the Forest Health Southern Regional Extension Forestry webinar series. (http://southernforesthealth.net/webinars)

Doug Jacobs chaired the first session of the Forest Seedling Root Symposium presented by the Western Forestry and Conservation Association in October. (https://westernforestry.org/past-conferences/forest-seedling-root-development-and-function-for-reforestation-and-restoration)

ANNUAL ADVISORY COMMITTEE MEETING

In October, HTIRC hosted the HTIRC advisory committee. Topics presented by research scientists included updates of ongoing funded projects and a field demonstration of digital forestry equipment.

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 eight PhD students and nine MS students with HTIRC funds. Four students graduated this year:

HTIRC students who graduated in 2021

- Geoffrey Williams (PhD)
- Sarah Cuprewich (MS)
- Benjamin Rivera (MS)
- Recep (Rich) Yildiz (MS)

2021 HTIRC OPERATIONAL TREE IMPROVEMENT REPORT

Jim McKenna retired in August 2021 as the HTIRC's Operational Tree Breeder. We wish him well and will sorely miss his wealth of information, experience and humor. Caleb Kell has taken up responsibility for the HTIRC's tree improvement program and will further build on the great foundation Jim has established.

NEW PLANTINGS

Union County Black Walnut/Black Cherry/Butternut silvicultural trial – 1,800 trees planted in collaboration with the Indiana branch of The Nature Conservancy. This planting will test performance of HTIRC black cherry, walnut and butternut lines in a mixed planting setting typical of those installed by consultant foresters across Indiana.

Lugar Resistant Butternut Orchard – A butternut breeding orchard was established at the Lugar farm with grafted canker-resistant selections from HTIRC butternut screening blocks. Nested within the Lugar American beech orchard, this new planting brings the HTIRC closer to its goal of developing a canker-resistant butternut population.

Lugar Grafted American Chestnut Orchard – This new orchard contains most of the accessions from the Duke orchard at Martell and new accessions sent to the HTIRC by the American Chestnut Foundation in a blight-free environment. This block is the future site of the HTIRC's chestnut breeding efforts.

Martell Butternut Screening Block V – Progeny from the HTIRC's butternut orchard in Pinney Purdue Agricultural Center (PAC) were planted at a new butternut canker screening block at Martell to further develop additional canker-resistant butternut lines.

Clinton County American Chestnut Seedling Seed Orchard – New American chestnut seedlings (48) were added and dead trees in the 2020 planting were replanted with surplus butternut progeny from the Pinney PAC seed orchard.

SELECTIONS

We made numerous new butternut and hybrid butternut selections based on 10-year butternut canker disease ratings. We collected scion wood from 50 of the best trees along with the best-formed hybrid progeny selected from our 2013 hybrid butternut progeny test in Coldwater, MI.

GRAFTING

White oak – Two new veneer selections and 13 HTIRC accessions with two or fewer copies were grafted onto swamp white oak rootstock and will be outplanted at the Lugar farm in spring 2022.

Butternut – 54 new butternut selections were grafted, but there was exceptionally poor graft take (10%) due to weak wood from the hard frost on May 19, 2020. Successful grafts will be outplanted at the Lugar Farm in spring 2022.

Chestnut – Accessions from the 2020 TACF scion donation and the Duke block with fewer than three clones were grafted to safeguard against losses from delayed graft incompatibility. They will be outplanted at the Lugar farm in spring 2022.

CROSS POLLINATION

The HTIRC continued to cross its American chestnut collection with transgenic pollen supplied by SUNY and the University of New England in 2021. The 17-year cicada outbreak peaked during optimum pollination time, and oviposition damage killed many pollinated flowers. Despite this challenge, 16 new transgenic lines were produced, and the seed was shipped back to SUNY for their transgenic breeding efforts.

SEED HARVEST

A bumper crop of black walnut was harvested from the orchards and clone banks at Martell and Lugar. Seed from 58 untested black walnut lines was planted at the Vallonia State Nursery for establishment of new progeny tests in 2023. HTIRC and Purdue FNR contributed more than 400 bushels of select and bed-run black walnut seed to the state nursery as well. White oak had a respectable crop, and 18 lines were sown at Vallonia for progeny testing in 2024.

LOOKING FORWARD

The HTIRC is looking for excellent white oak selections and surviving American chestnut from Indiana and Illinois for the 2023 grafting season. If you know of an outstanding white oak or a surviving American chestnut, contact Caleb Kell at ckell@purdue.edu.

APPENDIX

2021 RESEARCH PUBLICATIONS

HTIRC-related research papers published in 2021 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/

Ethington, M.W., G.P. Hughes, N.R. VanDerLaan, M.D. Ginzel. 2021. Chemically-mediated colonization of black cherry by the peach bark beetle, *Phloeotribus liminaris*. Journal of Chemical Ecology. 47 (3): 303-312.

Huang, S., L.N. Tang, J.P. Hupy, Y. Wang, and G.F. Shao. 2021. Commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. Journal of Forestry Research. 32: 1–6.

Juzwik, J., A. Yang, S. Heller, M. Moore, Z Chen, M. White, H. Wantuch, M.D. Ginzel, R. Mack. 2021. Vacuum steam treatment effectiveness for eradication of the Thousand cankers disease vector and pathogen in logs from diseased walnut trees. Journal of Economic Entomology. 114 (1): 100-111.

Lin, Y., J. Liu, S. Fei, and A. Habib. 2021. Leaf-off and Leaf-on UAV LiDAR Surveys for Single Tree Inventory in Forest Plantations. Drones. 5(4): 115. https://doi.org/10.3390/drones5040115.

Lin, Y., Shao, J., Shin, Y., Saka, Z., Joseph, M., Manish, R., Fei, S., and Habib, A. 2021. Comparative Analysis of Multi-platform, Multi-resolution, and Multi-temporal LiDAR Data for Forest Inventory. (*Submitted to Remote Sensing Journal*.)

Miller, Z., J. Hupy, A. Chandrasekaran, G. Shao, and S. Fei. 2021. Application of Post-Processing Kinematic Methods with UAS Remote Sensing in Forest Ecosystems. Journal of Forestry. 119: 454–466.

Miller, Zachary. 2021. Quantification of Land Cover Surrounding Planned Disturbances using UAS Imagery. M.S. Thesis, School of Aviation and Transportation Technology, Purdue University

Ravi, R., Y. Lin, R. Manish, S. Fei, and A. Habib. 2021. Backpack and UAV LiDAR Data Fusion for Trajectory Enhancement and Derivation of Accurate Forest Inventory Metrics. (Submitted to ISPRS Journal for Photogrammetry and Remote Sensing.)

Shao, G.F., L.N. Tang, and H. Zhang. 2021. Introducing Image Classification Efficacies. IEEE Access 9: 134809-134816.

Williams, G.W., M.D. Ginzel. Competitive advantage of *Geosmithia morbida* in low-moisture wood may explain historical outbreaks of Thousand cankers disease and predict the future fate of *Juglans nigra*. Frontiers in Forests and Global Change. 4.

HTIRC
HARDWOOD TREE IMPROVEMENT
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