HTIRC™
HARDWOOD TREE IMPROVEMENT
& REGENERATION CENTER

2022 ANNUAL REPORT

In partnership with:

PURDUE UNIVERSITY | Forestry and Natural Resources

USDA Forest Service
U.S. DEPARTMENT OF AGRICULTURE

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ABOUT HTIRC

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).

HTIRC's strategic objectives are 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.

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.

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. 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.

Hardwood Tree Improvement and Regeneration Center
Purdue University

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2022 HIGHLIGHTS

PERSONNEL

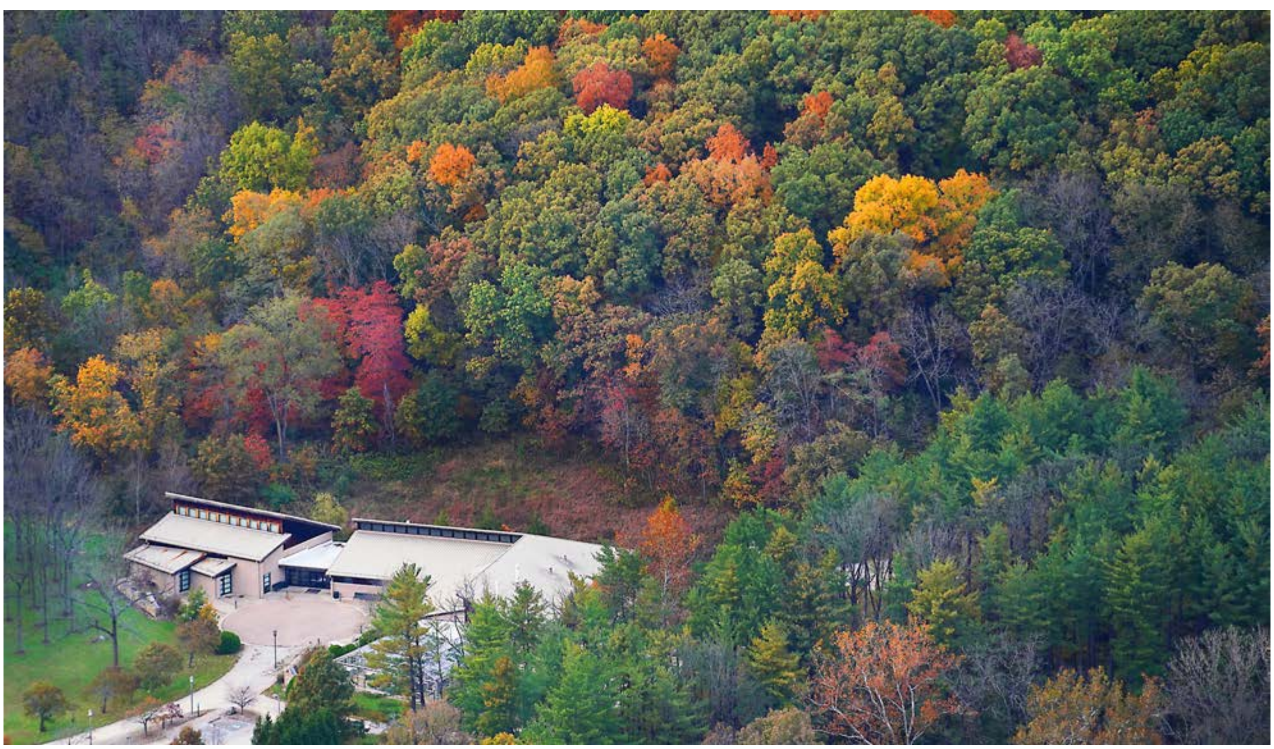
- Morgan Furze, plant physiologist, joined the HTIRC as a project scientist.
- We bid farewell to Wes Schempf, HTIRC Research and Communications Coordinator, as he moved on to the Texas A&M Tree Improvement Program.
- Administrative assistant Janis Gosewehr retired after 33 years at Purdue and 22 years working for the HTIRC. We appreciate all of Janis's efforts and wish her the very best in her retirement.

RESEARCH

- Integrated Digital Forestry (iDiF) initiative was selected to be part of the Plant Science 2.0 institute in Purdue's Next Moves over the next five years and has garnered over $20M in grants – including a recent award from the USDA NIFA Sustainable Agriculture System (SAS) program focused on promoting economic resilience and sustainability of eastern US forests.
- HTIRC Executive Committee approved funding for two new research proposals:
  - eForester: AI-assisted smartphone app for automated tree inventory – Zhang, $150,000, 3 years
  - Integrating morphological, genotype, and chemotype based methods to support HTIRC butternut conservation and resistance breeding – Jacobs, $151,110, 3 years

EDUCATION/OUTREACH

- Aziz Ebrahimi successfully defended his PhD dissertation. Aziz has stayed on as a postdoc in FNR. Congrats, Aziz!
- Sarah Rademacher successfully defended her MS thesis. Congrats, Sarah!
- The Indiana Forest Product Price Report is returning, thanks to Purdue FNR's Dr. Mo Zhou. The report has been published since 1934, and past issues have been digitized and posted online at: https://foreststimberin.shinyapps.io/TimberPrice/.



EXECUTIVE COMMITTEE

To help us deliver on our strategic objectives, an 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 (USDA Forest Service)
- Dana Nelson (USDA Forest Service)
- Guillermo Pardillo (ArborAmerica)
- Jack Siefert (Indiana DNR)

PARTNERS AND COLLABORATORS

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 EASTERN REGION STATE, PRIVATE AND TRIBAL FORESTRY: Collaborates with states, other federal agencies, tribes, landowners, and other partners to protect, conserve, and manage forests and community trees across 20 Northeast and Midwest 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
Nathan Hilliard | Laboratory Manager
Elizabeth Jackson | Engagement Specialist
Patrick O'Neil | Genomics Laboratory Manager
Weston Schempf | Research and Communications Coordinator
Rhonda Taylor | Laboratory Manager

PROJECT SCIENTISTS

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

POSTDOCTORAL RESEARCH ASSOCIATES

Dennis Heejoon Choi
Rastiveis Heidar
Behrokh Nazeri
Indira Paudel
Bina Thapa
Andrei Toca
Jianmin Wang

GRADUATE STUDENTS

Molly Barrett | MS
Erin Bell | PhD
Olivia Bigham | MS
Aishwarya Chandrasekaran | PhD
Kelly French | PhD
Aziz Ebrahimi | PhD
Elias Bowers Gaffney | MS
Sayon Ghosh | MS
Scott Gula | PhD
Yunmei Huang | PhD
Brianne Innusa | MS
Ellie Joll | MS
Caleb Kell | MS
Bowen Li | MS
Alison Ochs | PhD
Minjee (Sylvia) Park | PhD
Summer Rathfon | MS
Tawn Speetjens | MS
Thad Swart | MS
Kelsey Tobin | PhD
Wang Xiang | PhD
Cameron Wingren | MS

TECHNICAL STAFF

Brian Beheler | Farms Manager
Don Carlson | Forester
Sarah Cuprewich | Research Assistant
Clayton Emerson | Assistant Property Manager
Caleb Kell | Research Forestry Technician
Caleb Redick | Research Associate
Ron Rathfon | Extension Forester
Rebekah Shupe | Research Associate
James Warren | USDA Forest Service, Biological Scientist

DIRECTOR'S REPORT

The Hardwood Tree Improvement & Regeneration Center continues to advance the research, teaching and Extension priorities outlined in our current strategic plan. Through our project-based funding model, we have supported 18 projects, including two new ones. In this annual report, we share progress reports on projects already underway and summaries of the newly funded projects, which our executive committee selected. A special thanks goes to the committee members for their vision and continued leadership and engagement. These research projects directly serve our strategic research objectives and also reflect our commitment to serving the needs of our stakeholders. We continue to support graduate students through our project-based funding model. Last year funds from the Fred M. van Eck Forestry Foundation for Purdue University were used to support nine HTIRC master's students, nine PhD students, five postdocs, six undergraduate research technicians and one high school student over the summer.

With support from the HTIRC, the integrated Digital Forestry (iDiF) group, led by Songlin Fei, leveraged this investment to garner wide interest at Purdue and beyond. The goal of this group is to apply digital technology and multidisciplinary expertise to measure, monitor and manage forests to maximize social, economic and ecological benefits. The iDiF initiative was selected to be part of the Plant Science 2.0 institute in Purdue's Next Moves over the next five years and has garnered over $20M in grants – including a recent award from the USDA NIFA Sustainable Agriculture System (SAS) program focused on promoting economic resilience and sustainability of eastern US forests.

This year we continued our involvement with the Center for Advanced Forest Systems. In 2009, the HTIRC, along with Oregon State University, co-founded the only forestry-based National Science Foundation (NSF) Industry/University Cooperative Research Center (I/UCRC). We are now in the third and final phase of CAFS, which continues our involvement through 2024.

This year we bid farewell to Wes Schempf as he moved on to the Texas A&M Tree Improvement Program. Wes was instrumental in coordinating research and communications for our center, and we look to fill his vacant position in the coming year. Janis Gosewehr, our longstanding clerical professional, retired at the end of the year. Janis worked at Purdue for more than 33 years and provided support to HTIRC since the beginning. I appreciate all of Janis's efforts, particular the care and attention she paid to our students, and wish her the very best in her retirement.

We remain committed to connecting our partners, collaborators, and stakeholders with the people, information, and products of the center through our technology-transfer efforts. In 2022, we produced and updated a variety of online resources, including videos on hardwood management, invasive species, and tree identification, and posted them on our website. We also shared the latest HTIRC information with landowners and/or natural resources professionals through a mix of online and in-person programs. We actively engaged with our partners and many other groups, agencies and organizations with similar goals and interests to understand management and information needs and facilitate distribution of research-based tree and forest management information to appropriate audiences. Guidance and input from such stakeholder groups is vital to the continued growth of the HTIRC and the research it supports. I look forward to continue working together to advance the mission of the HTIRC.

Best,

Matthew Ginzel
HTIRC Director

HTIRC
HARDWOOD TREE IMPROVEMENT & REGENERATION CENTER

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 has 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. 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.

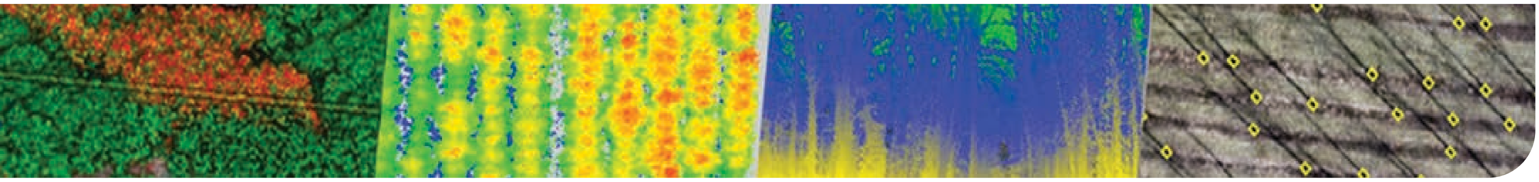
A CAFS Industrial Advisory Board (IAB) reviews ongoing and completed activities and selects new projects. In addition, the IAB provides input to NSF on the functioning of the Center. The IAB strongly influences the priority given to various research projects. Each university site appoints a representative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

In 2022, on June 7-8, we held our CAFS IAB annual meeting in Snoqualmie, Washington. It included a full day of presentations from CAFS scientists and a field tour. Our next IAB meeting will be June 21-22, 2023, in Louisville, Kentucky, and will feature white oak management.

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

INTEGRATED DIGITAL FORESTRY INITIATIVE (iDiF)



The Center for Digital Forestry, led by Songlin Fei, made major progress in 2022. The goal of the center is to leverage digital technology and multidisciplinary expertise to measure, monitor and manage urban and rural forests to maximize social, economic and ecological benefits. HTIRC's early and critical support helped digital forestry to be recognized as part of the Plant Science 2.0 institute in the Purdue's Next Moves initiatives in spring 2021.

The digital forestry team currently has 25 researchers, two professional staff members, eight postdocs, and about 40 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. Collaborating with groups within and outside Purdue, the Center for Digital Forestry recently secured two major grants, one from USDA AFRI Sustainable Agriculture Systems ($10M) and another from USDA-FPAC Climate Smart Commodities ($35M), boosting its research mission.

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

INVESTIGATORS

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

PROJECT OBJECTIVES

- 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 plantings. 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 efforts 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 growth data corresponding to the 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. This data is 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

- Six ≥ 0.5 ha sites chosen for study: black walnut (3), Northern red oak (3)
- Sites span two states: Indiana (4), Michigan (2)
- Local temperature and precipitation data obtained from 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.)
- Initial soil descriptions: The Natural Resources Conservation Service (NRCS) in Indiana map of soil descriptions (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054013).
- Soil classifications: NRCS soils site, 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/).

MODEL EVALUATION

- Wallace and Young model presumes black walnut tree heights can be used to predict soil depth.
- Heights and DBH will be collected for cross validation.
- Study results could significantly influence future forest management and plantation development efforts.

SITE AND STAND DATA TO INCLUDE

- Measurement data (height, DBH) and site characteristics (pH, soil depth (divided by organic layer and horizon), soil texture, and nutrient loads (N, P, K).
- Climate data (temperature, precipitation).
- 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

- Samples collected from all sites: 100% of samples submitted for analysis.
- Analysis timeframe: 6- to 8-month wait for data results (COVID-19 protocols limited employees and significantly reduced workflow within the soils lab).
- Data from 5 sites: walnut (2), Northern red oak (3) received and graphed with GIS.
- Observed traits show variability between walnut and Northern red oak.
- Expanded project to include investigation of the black walnut and Northern red oak microbiome.

STATISTICAL ANALYSIS

- Data have been analyzed for standard distribution (bin frequency).
- Height and DBH data have been analyzed with soil mineral data (ANCOVA).

DISSEMINATION / EXTENSION EFFORTS

Eleven oral presentations (NC State, Walnut Council, Alpha Kappa Alpha Sorority, Inc. (2), Soil Science Society of America (SSSA) (2), Southeast Purdue Agricultural Center (SEPAC), Potential collaborators (USDA Forest Service - Northern Research Station) (2), Potential collaborators (Purdue University) (2).

- Four poster presentations (HTIRC (2), American Society of Agronomy, International Society for Microbial Ecology)
- Two presentations to potential nationwide collaborators (CR-DEI Leadership (Washington Office, Forest Service (Northern & Southern Research Stations), various Southern Research Station University representatives)

MANUSCRIPTS IN PROGRESS (TITLES SUBJECT TO CHANGE)

- Impact of tree species on fungal community structure and function in Central Hardwoods Forest Region (CHFR) forest plantations. (Figure 1)
- Evaluation of bacterial and fungal community composition and biomass beneath black walnut and northern red oak plantations. (Figure 2)
- Site suitability in black walnut: A brief assessment of family performance. (Figure 3)
- Influence of soil traits on height growth in black walnut families: A comparison across sites. (Figure 4)

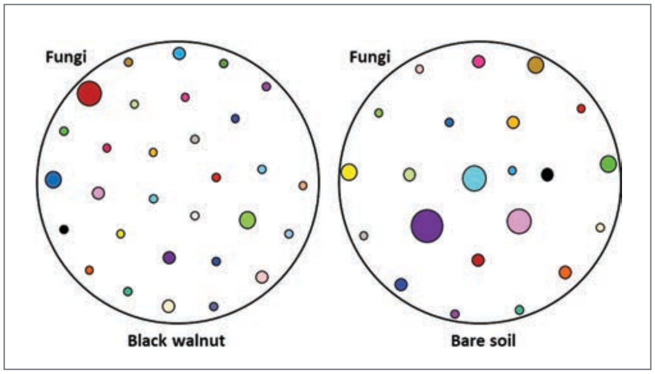


Figure 1. Illustrations of the differences in variety (color) and volume (size) of fungal communites in bare forest soil compared to beneath black walnut plantations.

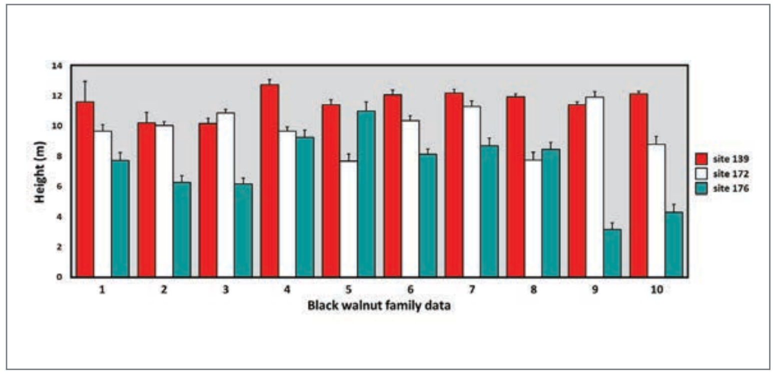


Figure 3. Differences in average height among 10 black walnut families at three plantation sites.

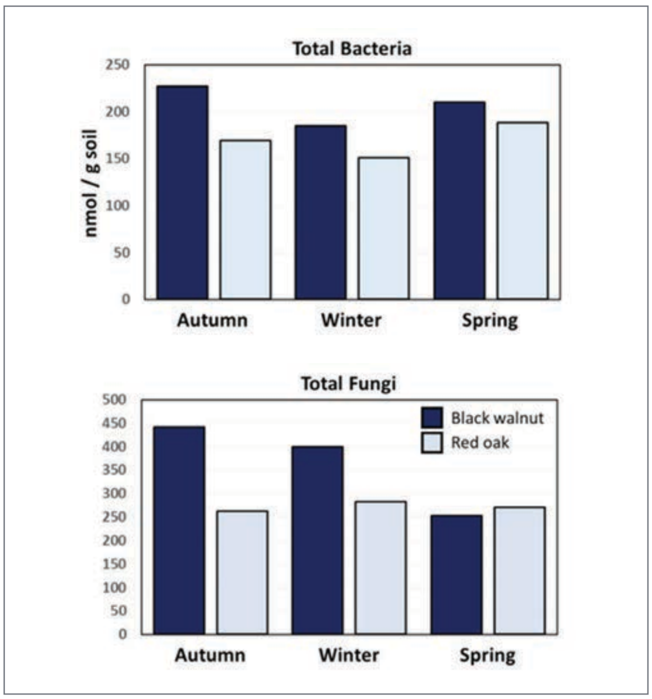


Figure 2. Measurements of total bacteria and total fungi populations in black walnut and Northern red oak populations.

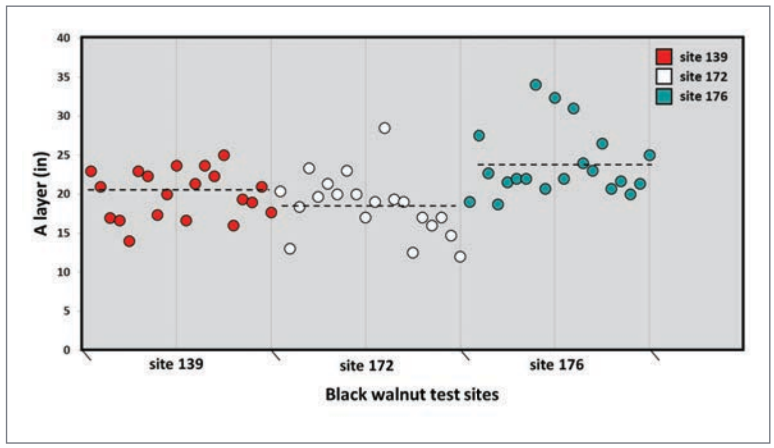


Figure 4. Variability in A layer depth at three different black walnut test sites.

FUTURE PLANS

- Continue efforts to finalize manuscripts and solicit more opportunities to present research to peers.
- Use analysis results to initiate further studies using these data.
- Overlay new soil analyses with coarse soil maps from the USDA Soil Conservation Service.
- Identify additional test sites to provide proof of concept.
- Presentations currently on the agenda: Northeastern Area Association of State Foresters Forest Utilization Committee, International Wood Collectors Society, Great Lakes chapter, and the Walnut Council (multiple states).

PARTNERS / COLLABORATORS

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

COLLABORATING INVESTIGATORS

- Carolyn “Carrie” Pike, Regeneration Specialist, USDA-FS, Northeastern Area State & Private Forestry, FNR, Purdue University
- Lenny Farlee, Sustaining Hardwood Extension Specialist, FNR, Purdue University
- John Kabrick, Research Forester, USDA-FS, NRS, Department of Agriculture, Food & Natural Resources, University of Missouri-Columbia
- Shalamar Armstrong, Assistant Professor, Department of Agronomy, Purdue University
- Mary Beth Adams, Research Soil Scientist, Emeritus, USDA-FS, NRS, Morgantown, West Virginia
- Juan Frene, Soil Scientist/Biotechnologist, University of Nottingham, Nottingham, United Kingdom
- Terrence Gardner, Soil Microbial Ecologist/Biogeochemist, Morehouse College, Atlanta, Georgia
- James “Jim” McKenna, Operational Tree Breeder (Retired), USDA-FS

USING TERRESTRIAL LASER SCANNING TO ASSESS TREE HEALTH AND QUALITY

INVESTIGATORS

- **Brady S. Hardiman**, *Associate 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 Terrestrial Laser Scanning (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 2022 to develop new tools, methods, and data products based on terrestrial and aerial lidar from forests. We collaborated with researchers in Purdue Civil Engineering and Computer Science to derive LiDAR metrics of tree and forest structure with strong linkages to ecosystem function. Funds were allocated to support three postdocs co-mentored by Drs. Hardiman and Fei: Dr. Heejoon (Dennis) Choi, Dr. Bina Thapa, and Dr. Jianmin Wang. All are working on interrelated projects developing new applications of LiDAR and other remotely-sensed data to characterize forest structure and improve understanding of its influence on forest functions. These and other related efforts have resulted in three publications in preparation and another that was published in 2022. HTIRC funding for these projects supported the collection and analysis of data that catalyzed new collaborations and resulted in two proposals that were submitted in 2022: one was submitted to the Purdue Ag-Engineering Collaboration Seed Grant program and was subsequently funded; a second is under review at the NIFA Engineering for Agricultural Production and Processing program.

APPROACH

- Terrestrial Laser Scanner (TLS): We collected LiDAR data using a variety of TLS systems, including a Lecia BLK360 Scanner (Lecia Geosystem AG), currently available in the Hardiman Lab, and a research-grade backpack LiDAR system built by Dr. Ayman Habib. These systems generate high-resolution scans of trees that allow estimation of an array of structural features related to tree health and quality and forest functions such as growth and production. Data were collected in natural and planted forest stands as well as urban forests.
- Aerial LiDAR: We are leveraging the availability of LiDAR data collected by conventional aircraft at forested sites throughout the U.S., including National Ecological Observatory Network (NEON) sites and the City of Chicago.

- Analysis: The limiting factor in successful use of LiDAR data to assess forest health and function from stem to stand is in the extraction of meaningful information from the raw 3D point clouds these instruments generate. Our various efforts are developing an array of new approaches to extract meaningful structural information. Our longer-term goal is to build and disseminate streamlined, user-friendly processing and analysis workflows, as well as publishing standardized datasets that can facilitate broader adoption of tree and forest structural information into a wide array of forest research and management efforts.

KEY FINDINGS AND ACCOMPLISHMENTS

Short-Term Effects of Moderate Severity Disturbances on Forest Canopy Structure. Choi,H.; LaRue, E.E.; Atkins, J.W.; Foster, J.R.; Hatala Matthes, J.; Fahey, R.T.; Thapa, B.; Fei, S.; and Hardiman, B.S. *In Preparation for* ***Ecography***

Moderate severity disturbances, those that do not result in stand replacement, play an essential role in ecosystem dynamics. Despite the prevalence of moderate severity disturbances and the significant impacts they impose on forest functioning, little is known about their effects on forest canopy structure and how these effects differ over time across a range of disturbance severities and disturbance types.

3D structure of forest canopy influences urban bird species diversity. Choi, H.; Shao, J.; Darling, L.; Fei, S.; Hardiman, B.S. *In Preparation for* ***Landscape and Urban Planning****.*

We calculated bird species diversity data derived from effort-correct observations recorded using the citizen-science app iNaturalist. Avian diversity was compared with 3D metrics of canopy structural complexity derived from high-resolution aerial LiDAR data covering the City of Chicago. Preliminary analysis indicates that local variation in bird species diversity is strongly associated with more structurally complex portions of the urban forest.

An Unsupervised Canopy-to-Root Pathing (UCRP) Tree Segmentation Algorithm for Automatic Forest Mapping. Carpenter, J.; Jung, J.; Oh, S.; Hardiman, B.; Fei, S. ***Remote Sensing***. 2022*,* 14*,* 4274*.*
https://doi.org/10.3390/rs14174274

Terrestrial laser scanners, unmanned aerial LiDAR, and unmanned aerial photogrammetry are increasingly becoming the go-to methods for forest analysis and mapping. The three-dimensionality of the point clouds generated by these technologies is ideal for capturing the structural features of trees such as trunk diameter, canopy volume, and biomass. This paper introduces an unsupervised method for segmenting individual trees from point clouds. The proposed algorithm's independence from a specific data modality, along with its robust performance in simple and complex forest environments and accurate segmentation results, makes it a promising step toward achieving reliable stem-mapping capabilities and, ultimately, toward building automatic forest inventory procedures.

Characterizing Urban Tree Species through Hyperspectral Images Using Machine Learning
Thapa, B.; Hardiman, B.S.; Darling, L.; Fei, S. *In preparation for* ***Remote Sensing of the Environment***.

Recent advances in analytical approaches and sensor technology have facilitated tree species classification using hyperspectral data. In this study, we demonstrate a framework to improve urban tree species identification using multi-temporal hyperspectral data. Our results show that hyperspectral data can be used to identify urban trees at the landscape level but requires careful consideration of time/season to capture species-specific phenology. Results from this study will improve management of urban forests through targeted species-specific management and may inform design of future sensors to include species-specific optimal wavelength bands.

FUTURE PLANS

Metrics of canopy structure for all forested NEON sites: 2015-2022. Wang, J.; Atkins, J.W.; LaRue, E.A.; Jung, J.; Fei, S.; Hardiman, B.S. *In preparation as a data paper in* ***Ecology***.
We are producing a data product that will be published as a data paper. This data product will consist of an array of ~15 canopy structural metrics derived from aerial LiDAR data acquired in annual surveys of all NEON sites. By producing and disseminating this first canopy structure data product of its kind, we hope to provide an interdisciplinary community of scientists and land managers easy access to standardized structural information and facilitate broader adoption of this crucial forest attribute into research and management efforts.

PARTNERS AND COLLABORATORS

- Ayman Habib, Professor, Civil Engineering, Purdue University
- Bedrich Benes, Professor of Computer Science, Purdue Computer Science
- Daniel Aliaga, Associate Professor of Computer Science, Purdue Computer Science
- Jinha Jung, Assistant Professor of Civil Engineering, Purdue Civil Engineering

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

INVESTIGATORS

- **Mike Saunders**, *Associate Professor, Forestry and Natural Resources, Purdue University, (msaunder@purdue.edu)*
- **Molly Barrett**, *Graduate Student, Forestry and Natural Resources, Purdue University*
- **Elias Gaffney**, *Graduate Student, Forestry and Natural Resources, Purdue University*

PROJECT OBJECTIVES

- Compare the interacting effects of prescribed fire and expanding group shelterwood harvesting on mid-term natural regeneration response; and
- Compare the short-term effects of light levels and interspecific competition on underplanted white oak in context to variable conditions in a natural forest (Crane NWSC) and more controlled conditions in a shade house (Lugar Tree Farm).

ABSTRACT

White oak (*Quercus alba*) is a species desired for its economically valuable timber as well as its ecological benefits. While white oak was once a dominant species across the Central Hardwood Region (CHR), various barriers to successful oak recruitment are leading to a precipitous shift in compositions of CHR forests, away from oak and hickory and toward maple, beech and other mesophytic species. Increased partial harvesting exacerbates this shift, as young white oaks fail to supplant dying or harvested mature individuals; white oak dominance will diminish rapidly in the next 50 years as a result. Compounding this issue, the regeneration ecology of white oak is, unfortunately, less studied than from its conspecific northern red oak (*Quercus rubra*). This research examines how natural and artificial white oak regeneration reacts to competition and light level to identify a suite of conditions best suited for the successful recruitment of young white oak into forest canopies.

APPROACH

Response of natural regeneration to fire and shelterwood harvesting

- In 2015, a replicated trial of two expanding group shelterwood regeneration systems was installed across eight sites at the Department of the Navy's NSA Crane installation near Crane, Indiana.
- In summer 2020, we documented 5-year growth responses using quadrats located on 400 permanent plots and 160 group-based transects on those sites.
- We continue to conduct analysis on the 2020 data.

Response of white oak to varying light and competition levels – Crane underplanting

- In summer 2020, we underplanted 1-0 and 2-0 white oak stock from variable seed sources into plots overlaying the boundary between canopy openings created by the shelterwood harvest to the unharvested matrix between groups (Figure 1). This created a gradient of overstory light levels that we could then superimpose a gradient of weeding treatments upon (i.e., no control, 2-year control, 4-year control), thereby creating an array of light and understory competition levels.
- We maintained the plots this year including periodic checks of the deer fence and application of herbicide and/or manual weeding in both 2-year and 4-year treatments.
- We continued to track survival and growth of planted seedlings through the second growing season. We also quantified competition levels using two-dimensional (quantifying woody species present) and three-

dimensional (quantifying functional group percent cover above a seedling's canopy) quadrat sampling methodologies, as well as through light levels captured with hemispherical photography.

Response of white oak to varying light and competition levels – Lugar shade house

- We planted 1-0 white oak and northern red oak stock beneath three levels of light exposure (10%, 30%, and 100%, or full sun) and intermixed with bush honeysuckle (*Lonicera maackii*) competition in a split-plot design (Figure 2).
- We measured survivorship, growth, foliar nutrient content, relative water content, leaf area and thickness, chlorophyll content, and photosynthetic activity of both oak species.

Figure 1. Example of underplanting plot at Crane.

Figure 2. The shade house study at Lugar.

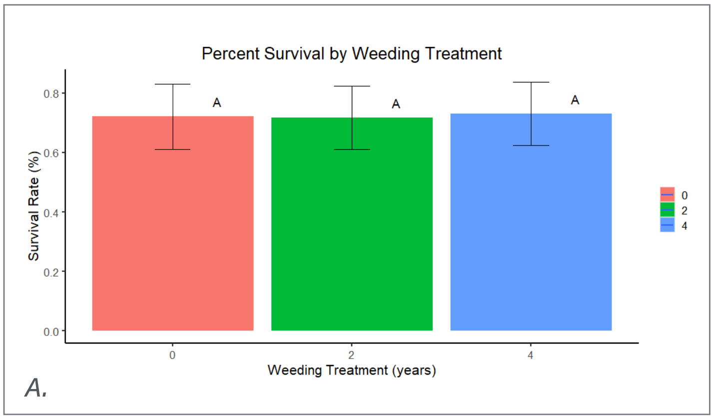
KEY FINDINGS

Response of white oak to varying light and competition levels – Crane underplanting

- Weeding treatments have not had a significant impact on survival (Figure 3A), but have increased diameter growth (Figure 3B). Conversely, height growth is higher without weeding (Figure 3C), suggesting a tradeoff in aboveground versus belowground growth in response to understory competition.
- There were some differences in two-year growth and survival responses based on seed source:
  - Illinois (IL) and Arkansas (AR) stocks have significantly higher survival rates than Wisconsin (WI) stock. Surprisingly, Indiana (IN) stock has the lowest rate of survival (Figure 4A).
  - IL stock has increased in diameter the most, with IL and AR stocks growing at similar rates. WI stock grew significantly less in diameter (Figure 4B).
  - IN stock has grown the most in height followed by IL and then AR stock. WI stock has declined in height (i.e., negative height growth) due to higher rates of top dieback and stem breakage than other seed stocks (Figure 4C).

Response of white oak to varying light and competition levels – Lugar shade house

- We have not conducted a detailed analysis with the first-year data, but generally responses were contradictory, likely reflecting planting shock or similar issues. Of note:
  - Light levels and presence of competition did not have significant impacts on diameter growth of either oak species.
  - Seedlings planted in full sun had less height growth than those grown in shade houses.
  - Seedlings with honeysuckle competition had less height growth than those without competition.
- In this study, honeysuckle competition is not allowed to overtop seedlings, indicating any difference in oak growth due to the presence of honeysuckle is largely due to belowground competition.



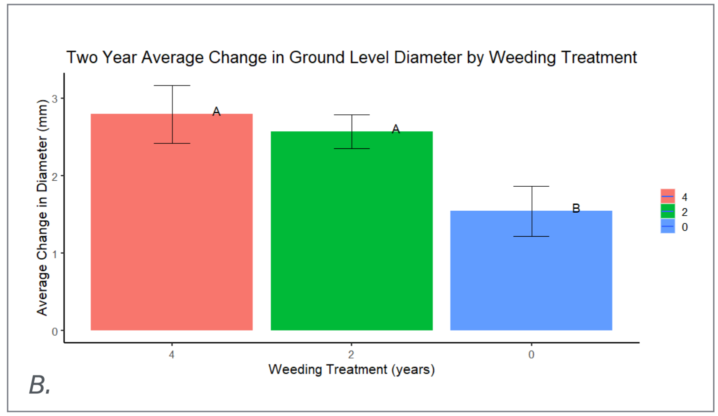
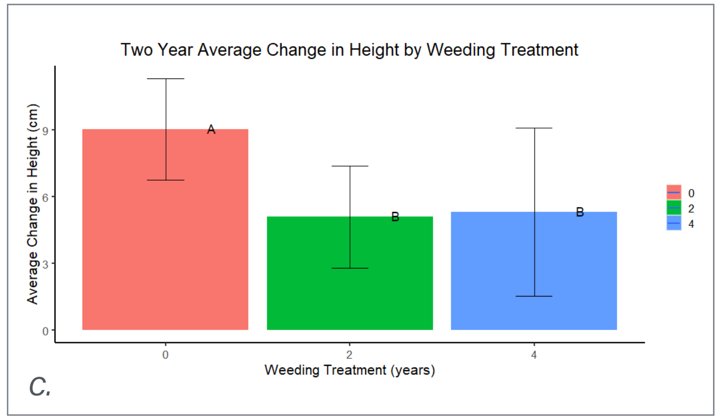
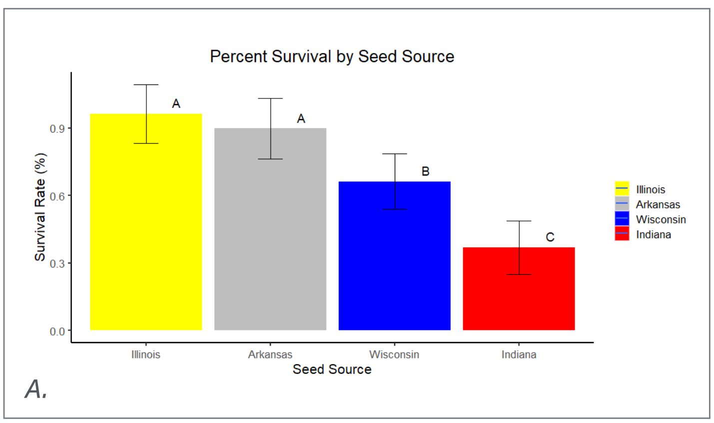


Figure 3. Two-year average (±standard error) seedling survival (A), groundline diameter growth (B) and height growth (C) by weeding treatment (0 = control). Treatments with the same letter are not significantly different at p = 0.05.





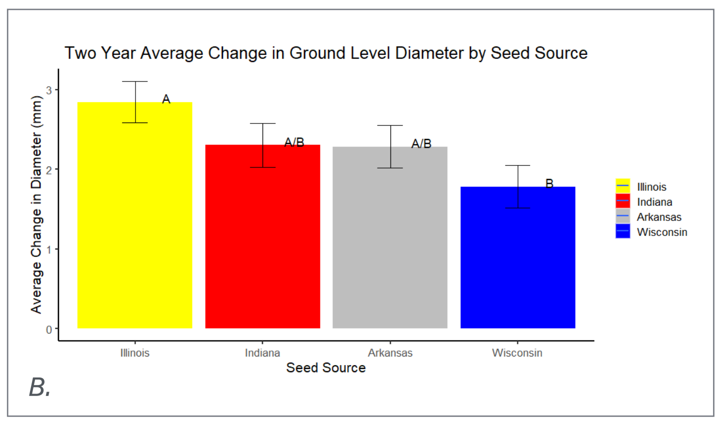
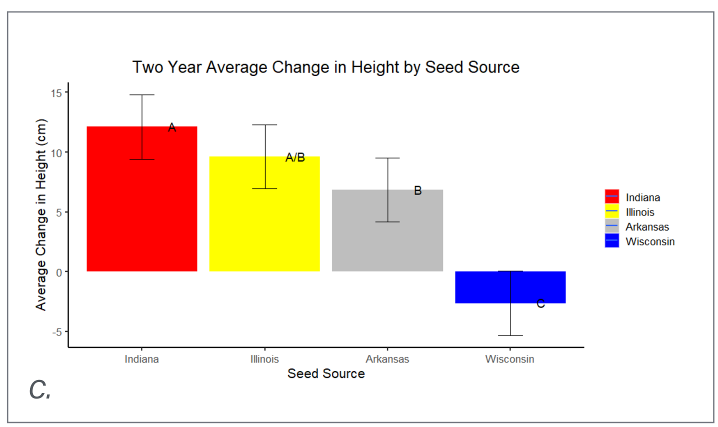


Figure 4. Two-year average (±standard error) seedling survival (A), groundline diameter growth (B) and height growth (C) by seed source. Treatments with the same letter are not significantly different at p = 0.05.



FUTURE PLANS

Response of natural regeneration to fire and shelterwood harvesting

- Finish analysis and write report (Barrett). Develop report into a peer-reviewed manuscript.

Response of white oak to varying light and competition levels – Crane underplanting

- Continue to monitor growth and survival measures of those seedlings planted at Crane while maintaining fencing and competition control.
- Analyze 3-year data and report results as a MS thesis chapter (Gaffney).

Response of white oak to varying light and competition levels – Lugar shade house

- Destructively harvest both northern red and white oak seedlings planted to examine biomass partitioning.
- Continue to monitor growth, survival, foliar nutrient and water quantities, as well as physiological measures for shade tent study oaks planted at Lugar for at least one more year.
- Analyze 2-year data and report results as a M.S. thesis chapter (Gaffney).

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.

PRODUCTIVITY-DIVERSITY RELATIONSHIPS IN HARDWOOD PLANTATIONS

INVESTIGATORS

- **Douglass F. Jacobs**, *Fred M. van Eck Professor of Forest Biology, Forestry and Natural Resources, Purdue University (djacobs@purdue.edu)*
- **John Couture**, *Associate Professor, Entomology, Purdue University*
- **Lenny Farlee**, *Sustaining Hardwood Extension Specialist, Forestry and Natural Resources, Purdue University*
- **Brady Hardiman**, *Associate Professor, Forestry and Natural Resources, Purdue University*
- **Gordon McNickle**, *Assistant Professor, Botany and Plant Pathology, Purdue University*

PROJECT OBJECTIVES

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 at Martell Forest of three fine hardwood species planted as monocultures and species mixtures at varying densities, we characterized 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 continue to disseminate findings to landowners in the Midwest with Extension field days and programs.

SUMMARY OF ACCOMPLISHMENTS

In 2022, one HTIRC graduate student and one research associate (Caleb Redick) continued their research on this project. Kliffi Blackstone (PhD, McNickle) is evaluating leaf litter, tree growth, dendrochronology, and physiological traits. Caleb Redick led installation of a new study installation at Purdue FNR's Hermann reserve. Madeline Montague (MS, Jacobs) studied belowground processes and successfully defended her MS thesis in

2021; her first thesis chapter was published in Forest Ecology and Management during 2022. Taylor Nelson (MS, Couture) examined canopy processes and successfully defended her MS thesis in 2021; her first thesis chapter on the influence of diversity and competition on nitrogen resorption efficiencies is in review in Ecosphere. Below, we summarize our specific accomplishments in 2022 related to the project objectives.

APPROACH

NET PRIMARY PRODUCTIVITY (NPP)

- Partitioned 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 was 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 were 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.

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 were 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.

ENVIRONMENTAL EFFECTS

- Datalogger network was upgraded to a new model capable of uploading data in real time.
- Solar-powered dataloggers ran a suite of sensors that measured light, air temperature, relative humidity, volumetric soil water, and soil water potential at 5-minute intervals beginning June 2019.
- Measurements were uploaded to the cloud daily via cellular uplink and available to all project researchers through a web interface.
- Leica BLK360 terrestrial laser scanner (TLS) was used to acquire a second round of 3D LiDAR point clouds from the center of each of 63 plots in the study design.

HERMANN RESERVE PLANTING

- Planted 9,240 trees in spring 2021 across six replicate blocks (~17 acres) at Purdue FNR's Hermann Reserve.
- Eight hardwood tree species were planted at four densities (1m×1m, 2m×2m, 3m×3m, and open-grown).
- Fences were constructed July 2021 and continue to be maintained.
- Herbicide was applied to vegetation before planting as well as pre-emergent herbicide in 2022. Mowing is being performed to control weeds between rows.
- Initial measurements were collected July 2021 and first-year survival was measured in summer 2022.
- Growth and survival will be measured in 2023 and site maintenance will continue long-term.

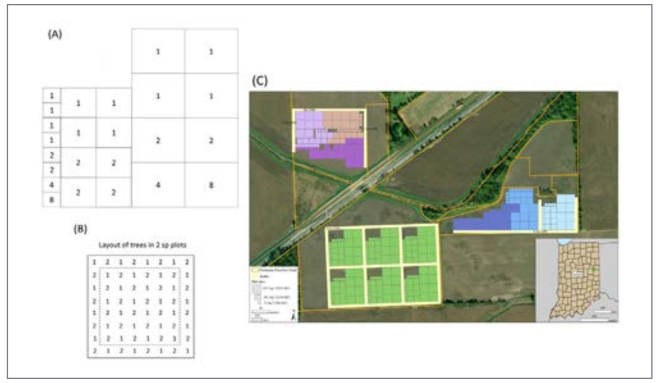


Figure 1. Planting design for the Hermann property.

Figure 2. Overhead drone photo of Hermann property after 2021 planting.

Figure 3. Four-species mix at Hermann planting after 1 year (3m×3m spacing).

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.
- One of Madeline Montague's MS thesis chapters was published in 2022: Montague MS, Landhäusser SM, McNickle GG, Jacobs DF. 2022. Preferential allocation of carbohydrate reserves belowground supports disturbance- based management of American chestnut (Castanea dentata). Forest Ecology and Management 509:120078.

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 (in review at Ecosphere).

- Outcomes suggest that trees adjust physiological process to conserve foliar nitrogen, as opposed to losing it in leaf litter, when in the presence of other individuals who take up soil nitrogen in a similar manner (in review at Ecosphere).
- Results 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 was 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 on the Martell Forest site using the aforementioned 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 a new trial to complement the experiment at Martell Forest. This was installed in spring 2021 across ~17 acres at Hermann Reserve, with eight hardwood tree species planted at four densities (1m×1m, 2m×2m, 3m×3m, and open-grown). This trial will provide an opportunity to examine how these species compare to the Martell results in terms of coexistence using the Modern Coexistence Theory.
- The second of Madeline Montague's MS thesis experiments will be submitted for publication in 2023.

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

INVESTIGATORS

- **Michael Jenkins**, *Professor, Forestry and Natural Resources, Purdue University (jenkinma@purdue.edu)*
- **Pierre-Luc Chagnon**, *Soil scientist, Agriculture and Agri-Food Canada*
- **Lenny Farlee**, *Sustaining Hardwood 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 arbuscular mycorrhizal (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 (*Lonicera 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

We completed experiments to address objective 1 and are currently analyzing data. Seeds of native species collected in Tippecanoe County, Indiana, in 2021 were germinated for use in experiments to address objectives 2 and 3. We were unable to germinate some of the tree species and were also unable to germinate *Lonicera* seedlings, although we were able to successfully do so previously. We have had to modify our experiments for objective 2 and will attempt to germinate seeds again for the objective 3 experiments. Our initial results show that *Lonicera* germinated better in all soil inoculum, regardless of invasion or treatment history, compared to sterile soil. This suggests that, while the species is a generalist, *Lonicera* depends upon soil biota to sustain growth and survival.

APPROACH

OBJECTIVE 1:

- In 2022, we completed a growth chamber experiment where *Lonicera* was grown in various soil inocula collected from five different sites in West Lafayette.
- DNA has been extracted from all inocula and sent to CERMO at UQAM facilities in Montreal (QC, Canada) for next-generation sequencing (characterization of soil fungal communities using general primers targeting the ITS1 fragment). The raw sequence reads have been treated using a standard in-house bioinformatic pipeline, Université de Montréal by Coralie Paŕe-Ricard (MSc student in Chagnon's lab).
- We are preparing the final data analyses linking fungal community composition with *Lonicera* performance.

OBJECTIVE 2:

- In both 2020 and 2021, conditions were far from ideal regarding border crossing. In 2021, we obtained an authorization from the Royal Botanical Garden in Southern Ontario to sample their invasive population of *Lonicera* and neighboring roots from native vegetation.
- Once the border reopened, a similar sampling design was used in West Lafayette in summer 2022. For both sets of samples, we isolated and thoroughly washed individual root fragments, and extracted genomic DNA from these using a homemade high-throughput protocol. These DNA extracts have been sent to the CERMO-UQAM sequencing facility for Sanger sequencing.
- After sequencing, we will pool fragments by species for each sampling site (i.e., the Ontario site altogether and the five distinct sites in West Lafayette, total n = six sites), and conduct a more thorough DNA extraction using a commercial kit including bead-milling of root tissues, to get the majority of root fungal endophytes. In winter-spring 2023, these DNA extracts will be sequenced using Illumina MiSeq technology and analyzed.
- This objective also included a companion plant-soil feedback experiment to follow up on the environmental DNA analyses outlined above. To determine if high levels of pathogen sharing would lead to negative plant-soil feedbacks between *Lonicera* and nearby native hardwoods, we collected seeds from different hardwoods in 2022 (sugar maple (*Acer saccharum*), pignut hickory (*Carya glabra*), black walnut (*Juglans nigra*), northern red oak (*Quercus rubra*), white oak (*Quercus alba*), honey locust (*Gleditsia triacanthos*), and white ash (*Fraxinus americana*)), along with *Lonicera* berries, and set them to germinate at Université de Montréal. Our germination success for some tree species and *Lonicera* was poor.

OBJECTIVE 3

- Because this objective planned to use seedlings unsuccessfully germinated for objective 2, we will try buying or collecting new seed stocks to initiate seedlings and perform the experiment in mesocosms.
- While we initially planned to examine 15N sharing in the mycorrhizal network in the field, another ongoing project in PL Chagnon's lab has found this approach to be riskier than a mesocosm approach where confounding factors could be better controlled.

KEY FINDINGS

OBJECTIVE 1

- *Lonicera* performed better with all inocula as compared with the heat-sterilized soil, suggesting its reliance on soil biota to ensure growth.
- However, in line with its invasive nature, it was not necessarily influenced by the origin of the inoculum. *Lonicera* was also found to be highly colonized by mycorrhizal fungi (*arbuscular mycorrhizal*), which suggests its heavy investment into the symbiosis, even for tiny first-year seedlings.
- It will be interesting to see if it shares mycorrhizal partners with other hardwoods and understory plants of the region, which will be addressed using samples from objective 2.

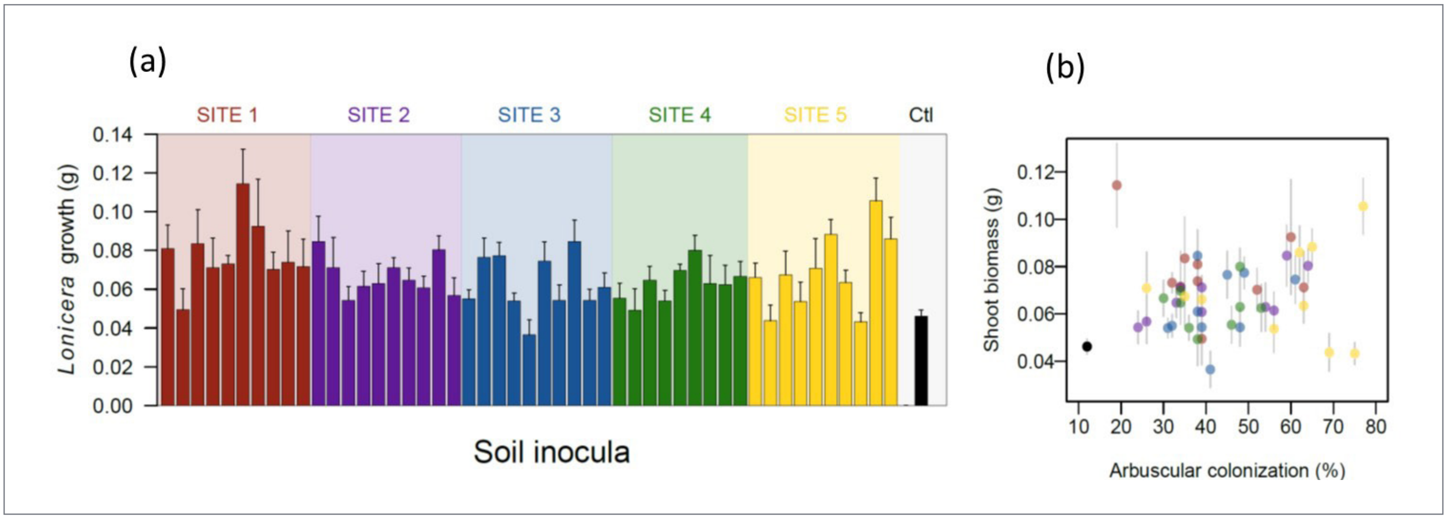


Figure 1. Lonicera (a) performance and (b) mycorrhizal colonization when inoculated with living soils collected from five different sites in West Lafayette, Indiana (color-coded).

OBJECTIVE 2

- We had mixed success with species germination. In phase 1, some species germinated with very high success (sugar maple, white ash, honey locust, and northern red oak), but some were inconsistent and could not be kept in the design (white oak and pignut hickory). Ironically, despite the tremendous number of seeds set to germinate, the variety of stratification conditions tested, the very successful germination in our 2019 trial, and the invasive nature of the plant, none of the *Lonicera* seeds germinated. The second phase of the experiment began last December, and again *Lonicera* did not germinate, and the red oak seeds developed mold.
- As a result, the experimental design is more modest than what was anticipated, and more importantly cannot include *Lonicera*. We are hoping to purchase new seed stocks in 2023 and to re-try the whole process all over again. The current MSc student will have graduated, but another student should be hired by PL Chagnon and paid through alternative research funds.

FUTURE PLANS

- Winter-spring 2023 – Objective 1: complete analysis and prepare manuscripts for submission.
- Spring 2023 – Objective 2: Upon receipt of Sanger sequencing data, treat the root fragments from the field to extract their DNA and get them ready for Illumin MiSeq sequencing.
- Spring 2023 – Objective 2: Harvest the first trial of plant-soil feedback experiment, which although incomplete, will convey interesting information about plant-soil feedback dynamics in alfisols among native hardwoods.
- Spring-summer 2023 – Objective 2 and 3: Start hardwood and *Lonicera* seedlings to do another trial for the plant-soil feedback experiment and for the mesocosm preparation for objective 3.
- Summer 2023 – Objective 2: Illumina MiSeq molecular data analysis (bioinformatics and downstream statistics) and manuscript writing.
- Fall 2023-winter 2024 – Objective 3: Completion of the mesocosm experiment with 15N labelling and tracing with or without *Lonicera* eradication.

TREE INVENTORY WITH AERIAL REMOTE SENSING

INVESTIGATORS

- **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 biometrics 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 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 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 detecting 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 multirotor 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

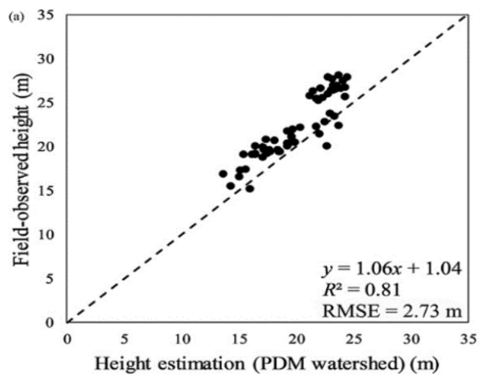
Objective 1: Two efforts have been made related to low-density LiDAR-based tree delineation. The first is to test the delineation of plantation trees with low-density LiDAR. We have successfully developed an algorithm to delineate a 60-year-old red oak plantation (Shao *et al.* 2018) and connected the 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, for which 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 published in Remote Sensing (Oh *et al.* 2022).

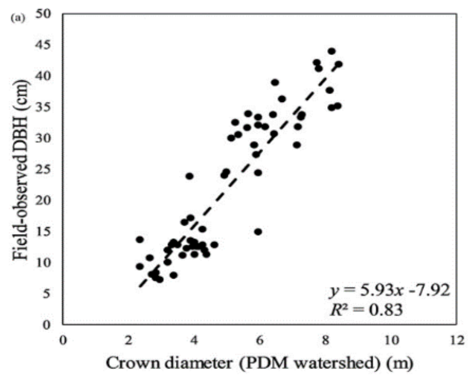
Objective 2: Regarding the effort of using UAS orthophotos, we have developed an algorithm along with a website for UAS orthophoto-based tree delineating for plantation forest, and published two manuscripts (Miller *et al.* 2021, Chandrasekaran *et al.* 2022). We also recently made a breakthrough in successfully creating a 3D cloud of trees, which allows the delineation of deciduous trees in natural forests (Carpenter *et al.* 2022).

Objective 3: Research findings have been disseminated through publications, invited and contributed presentations, and stakeholder meetings. More importantly, thanks to 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 been awarded a total of $20M in grants.

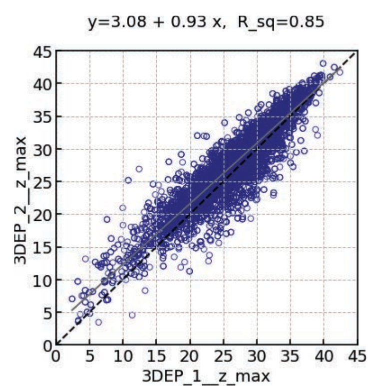
KEY FINDINGS/ACCOMPLISHMENTS

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

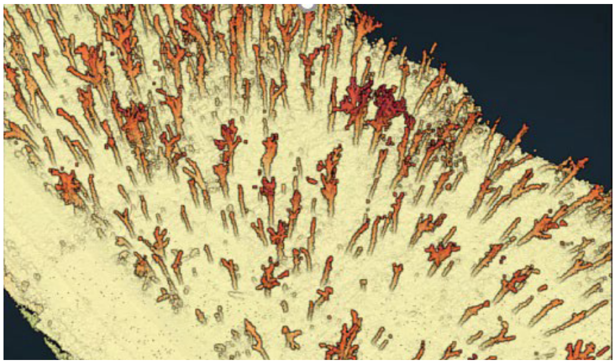




2. Low-density LiDAR can provide accurate tree height measure (Oh *et al*., under review in *Remote Sensing*)



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 25 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://ag.purdue.edu/digital-forestry/) highlighting the team and ongoing project.

   Data Portal. We have developed a web portal (https://digitalforestry.org/) to host and disseminate remote sensing data.

   Plant Science 2.0. We have been selected as part of the Purdue Next Moves.

   External Funding. iDiF is part of the $35M Climate Smart Commodities project (~$10M for Purdue's portion) and is leading another $10M Sustainable Agriculture Systems project.

   Annual Retreat. We have hosted two annual retreats (close to 200 participants) to showcase our findings.

   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 at Indianapolis.

   FIA Annual Meeting. We were invited to provide a keynote presentation and several organized presentations at this meeting. We disseminated our research findings to over 300 managers, researchers, and practitioners.

PUBLICATIONS

1. Shao, G., G.F. Shao, and S. Fei. 2018. Delineation of individual deciduous trees in plantations with low-density LiDAR data. *International Journal of Remote Sensing* 40: 346-363.
2. LaRue, E.A., B.S. Hardiman, J.M. Elliott, and S. Fei. 2019. Structural diversity as a predictor of ecosystem function. *Environmental Research Letters* 14: 114011
3. 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.
4. Oh, S. et al*.* 2022. Canopy height model generation and validation using USGS 3DEP LiDAR data in Indiana, USA. *Remote Sensing.* 14 (4), 935.
5. Chandrasekaran, A. et al. 2022. Automated inventory of broadleaf tree plantations with UAS imagery. *Remote Sensing* 14(8), 1931
6. Carpenter, J. et al. 2022. An Unsupervised Canopy-to-Root Pathing (UCRP) Tree Segmentation Algorithm for Automatic Forest Mapping. *Remote Sensing*. 14(17), 4274.

PRESENTATIONS

1. Fei, S. Application of Digital Technology for Automated Tree Measurement. 2022 DNR Division of Forestry Annual Meeting. July 2022. – **Invited.**
2. Fei, S. et al. Structural diversity as a novel predictor for ecosystem productivity. Ecological Society of America Annual Meeting. Aug. 2022. – **Invited.**
3. Can We Automatically Measure Every Single Tree on the Planet? President's Council: Back-to-Class. Oct. 2021. **- Invited**
4. Integrated Digital Forestry at Purdue. Dean's Advisory Council. Sept. 2021. **- Invited**
5. Digital Solutions for Forest Inventories. 2021 FIA National Users Group Meeting. June 2021 (Virtual) **- Invited**
6. Emerging needs: Gaps, models, and scaling. 2020 FIA National User Group Meeting. Aug. 2020 (Virtual) **- Invited**
7. Modernizing Natural Resources Stewardship in Digital Age. The National Academy of Science, Engineering, and Medicine, Board on Agriculture and Natural Resources. June 2020 (Virtual) **- Invited**
8. Elliott, J.M., E.A. LaRue, J. Gallion, S. Fei. (2019). Understanding the Impacts of EAB and Forest Structure on Understory Plant Invasion. Poster presentation for US-International Association for Landscape Ecology, Fort Collins, CO. April 8
9. Gilbert, J., J. Knott, E.A. LaRue, C. Oswalt, S. Fei. (2019). Diversity of Forest Structure Across the United States. Poster Presentation at the US-IALE Annual Meeting. Fort Collins, CO, USA. April 8.

10. LaRue, E.A., B.S. Hardiman, J.M. Elliott*, S. Fei. (2019). Canopy structural diversity as a predictor of forest function in North America. US-IALE Annual Meeting. Fort Collins, CO, USA. April 8. **Invited Oral Presentation**
11. Elliott, JM, E.A. LaRue, J. Gallion, S. Fei. (2019). Understanding the Impacts of EAB and Forest Structure on Understory Plant Invasion. FIA Stakeholder Science Meeting, Knoxville, TN, November 20.
12. Eliopoulos, N. and G. Shao. Estimation of Tree Diameter at Breast Height Using Close Range Stereo Photogrammetry. FIA Stakeholder Science Meeting, Knoxville, TN, November 20.
13. Chandrasekaran, A., Z. Miller, J. Hupy, S. Fei, and G. Shao. Photogrammetric measurement of hardwood species at a stand level using RGB images from Unmanned aerial vehicle (UAV). FIA Stakeholder Science Meeting, Knoxville, TN, November 20.
14. Unleash the power of FIA data – opportunities, challenges, and future directions. FIA Stakeholders Meeting. Nov. 2019. Knoxville, TN – **Keynote speaker**

PARTNERS/COLLABORATORS

- Joseph P. Hupy, Associate Professor, School of Aviation 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

INVESTIGATORS

- **John Couture**, *Associate 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

We had three objectives in this proposal: 1) determine the ability of hyperspectral data to provide information related to tree status in response to abiotic and biotic stress, 2) assess the reliability of hyperspectral information to scale from leaf, to tree, to stand level measurements, and 3) evaluate the validity of hyperspectral data to characterize stress responses over different spatial scales in different geographic locations.

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 1-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 0.24 to 0.95 and normalized error ranging from 6% to 26%. 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 (Figure 1). The predictive models reliably estimated most leaf functional traits with external validation goodness-of-fit (R^2) ranging from 0.24 to 0.95 and normalized error ranging from 6% to 26%, where the highest R^2 was seen in leaf water content (%) and the lowest R^2 was found in leaf juglone concentration (%).

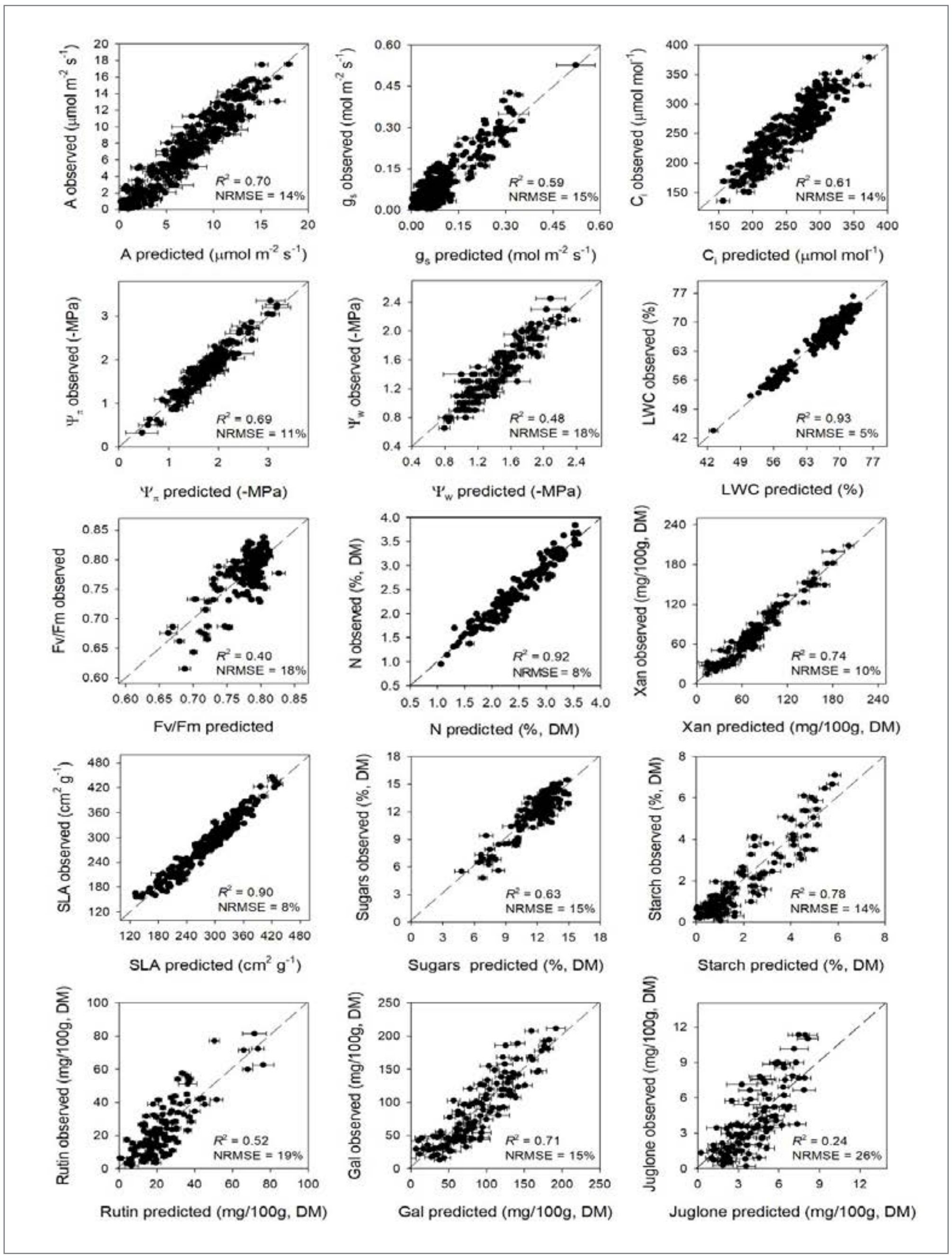
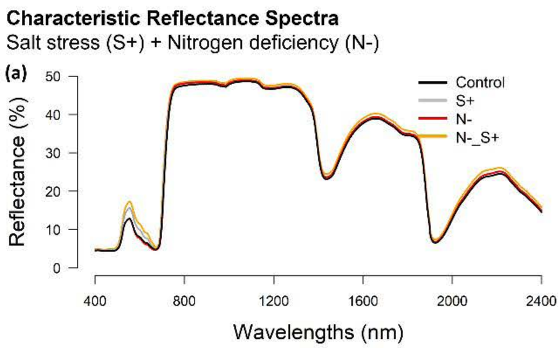


Figure 1. Observed vs predicted values of leaf traits for black walnut and northern red oak exposed to various stressors. Assimilation (A), stomatal conductance (g_s), intercellular CO_2 concentration (C_i), leaf osmotic potential (Ψ_π), leaf water potential (Ψ_w), leaf water content (LWC), maximum quantum yield of the photosystem II (F_v/F_m), nitrogen, xanthophyll (Xan), specific leaf area (SLA), sugars (glucose, fructose, sucrose), gallic acid (Gal). Error bars for predicted values represent the standard deviations generated from the 500 simulated models. The dashed line shows 1:1 relationship.

- Spectral data can classify salt and nutrient stress (Figure 2) and fungal inoculation (Figure 3) prior to the onset of visible symptoms. Salt stress increased reflectance in visible region, whereas nitrogen deficiency caused reflectance to increase in both visible and infrared regions. In the spectral range of 400-2400 nm, the mean overall classification accuracy was 0.90 ± 0.02 for calibration and 0.60 ± 0.07 for validation dataset (100 iterations). Control and nutrient stress were classified well (73 ± 17.8 %, 70 ± 15.0 %, respectively) but salt stress and salt and nutrient combined stress were more often confused for one another (44 ± 15.6 %, 53 ± 21.3 %, respectively). Geosmithia morbida-infected leaves showed increase of reflectance across the whole spectrum. In the spectral range of 400-1400 nm, the mean overall accuracy to classify healthy vs fungal infected group under natural forest soil or steam-treated soil were 0.74 ± 0.05 and 0.62 ± 0.18 for calibration and validation datasets. Geosmithia infected plants under forest soils were falsely classified as those under sterile soil, which can be explained by the similar spectra of Geosmithia infected groups.
- Ozone stress can be detected using spectral data prior to the onset of visible symptoms.



(b) Prediction

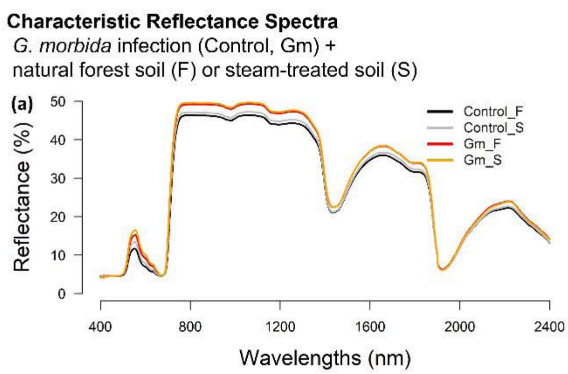
Reference	C (n=10)	S+ (n=10)	N- (n=9)	S+_N- (n=8)
C	**73.0 (±15.0)**	3.3 (±5.6)	21.0 (±13.0)	3.8 (±7.5)
S+	9.0 (±9.0)	**44.4 (±15.6)**	6.0 (±8.0)	45.0 (±17.5)
N-	25.0 (±13.0)	1.1 (±3.3)	**70.0 (±15.0)**	6.3 (±8.8)
S+_N-	2.0 (±5.0)	35.6 (±16.7)	3.0 (±6.0)	**52.5 (±21.3)**

(%)

PLS-DA classification
100 iterations

Calibration (80%, n=160)
Accuracy: **0.90 (±0.02)**
Validation (20%, n=37)
Accuracy: **0.60 (±0.07)**

Figure 2. (a) Characteristic reflectance spectra of control, salt stressed (S+), nitrogen deficiency (N-), and combined salt and nitrogen stressed groups (S+_N-). (b) A confusion matrix showing the results of the PLS-DA classification based on hyperspectral data to classify salt and nitrogen stressed groups. Yellow indicates correct classification.



(b) Prediction

Reference	C_F (n=7)	C_S (n=7)	Gm_F (n=5)	Gm_S (n=6)
C_F	**71.3 (±17.8)**	26.7 (±16.7)	1.7 (±4.6)	0.3 (±2.0)
C_S	17.9 (±14.1)	**80.0 (±1.5)**	0.0 (±0.0)	2.1 (±5.1)
Gm_F	6.4 (±10.5)	1.8 (±5.7)	**40.2 (±1.4)**	51.6 (±19.2)
Gm_S	0.5 (±2.8)	0.0 (±0.0)	42.0 (±21.1)	**57.5 (±1.7)**

(%)

PLS-DA classification
100 iterations

Calibration (80%, n=107)
Accuracy: **0.74 (±0.05)**
Validation (20%, n=25)
Accuracy: **0.62 (±0.18)**

Figure 3. (a) Characteristic reflectance spectra of control group under natural forest soil (Control_F), control group under steam-treated soil (Control_S), Geosmithia morbida-infected group under natural forest soil (Gm_F) and Geosmithia morbida-infected group under steam-treated soil (Gm_S). (b) A confusion matrix showing the results of the PLS-DA classification based on hyperspectral data to classify Geosmithia-infected groups under different soil conditions. Yellow indicates correct classification.

FUTURE PLANS

- Graduate student Sylvia Park will write a complete manuscript communicating outcomes from data presented in figures for a peer-reviewed publication. She will also continue and analyze data from other studies.

PARTNERS/COLLABORATORS

- University of Pisa, Italy

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

INVESTIGATORS

- **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,** *Associate Professor, Forestry and Natural Resources, Purdue University*
- **Jim Warren,** *Biological Scientist, USDA Forest Service*
- **Lenny Farlee,** *Sustaining Hardwood Extension Specialist, Forestry and Natural Resources, Purdue University*
- **Elizabeth Jackson,** *Engagement Specialist, HTIRC, Purdue University*
- **Sayon Ghosh*,** *Graduate Student, Forestry and Natural Resources, Purdue University*

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

PROJECT OBJECTIVES

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

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. To supplement the existing HTIRC database, new measurements of diameter at breast height (DBH), height, and crown radius were completed on selected HTIRC plots. A model of optimal stand establishment was developed previously and then dovetailed with a spatially explicit thinning model. Utilizing the Forest Vegetation Simulator (FVS) with these early-stage growth data, different scenarios of planting densities, site productivities and percentages of veneer sawlog were integrated to quantify the growth and profitability from the mid rotation until the final harvest. We found that without the threat of windthrows, the highest net present value (NPV) was $10,184 per acre for 6 feet by 6 feet planting on a high-quality site (SI = 100), harvested at 96 years with 20% veneer, with a discount rate of 3%. In contrast, financial losses could go as high as $41,547 per acre due to windthrows. Finally, we developed an interactive Extension tool for landowners to calculate the profitability under different scenarios.

APPROACH

1. Estimated the growth of black walnut under different planting densities and thinning treatments
    a) Developed a nonlinear multi-stage model of stand establishment that minimized establishment costs while ensuring free-to-grow status by year 5 and crown closure by year 10.
    b) Built a spatially-explicit thinning model to simulate crop tree release between years 10 and 20.
    c) Utilized the Forest Vegetation Simulator (FVS) for thinning at year 20 and between years 35 and 45 based on the crown competition factor, to leave only crop trees for the final harvest.
2. Estimated the total merchantable volume and derived profitability in 2-year intervals over a plantation's lifecycle.
3. Performed stochastic simulations of windthrow damages and estimated financial losses from the mid rotation until the final harvest.
4. Quantified the impacts of varying discount rates, site productivities, percentages of veneer-sawlog, and rotations on the stand value.
5. Utilized R shiny to develop an interactive Extension tool for landowners.

KEY FINDINGS

1. Ten years after a plantation was established, the average DBH of crop trees was 13.5 cm on edges and 13.2 cm on the interior. By adopting a thinning strategy of crop tree release in year 18, the DBH of crop trees ranged between 17.8 cm to 24.4 cm and that of non-crop trees ranged between 10 and 14.5 cm.
2. The highest net present value (NPV = $10,184 per acre, discount rate = 3%) was achieved with 6 feet by 6 feet black walnut planting, a rotation of 96 years, a highly productive site (SI =100) with 20% veneer by volume. Investments in black walnut plantations for the Central Hardwood Forest Region were not profitable when alternative investments offering 6% and 10% annual rates of return are available (Figure 1).
3. Under the threat of windthrows, higher productivity sites incurred relatively more losses than lower productivity sites for the same conditions. A longer rotation exposed a plantation to a higher probability of financial losses due to windthrow occurrence. The highest possible loss was $41,547 per acre for a 7 by 7 feet planting with 20% veneer, on a highly productive site (SI = 100) with a rotation of 96 years.
4. An interactive dashboard was developed and launched online for visualizing the stumpage value and timber volume over time with and without a windthrow, for different planting densities, site indices and veneer percentages of total merchantable volume (Figure 2).

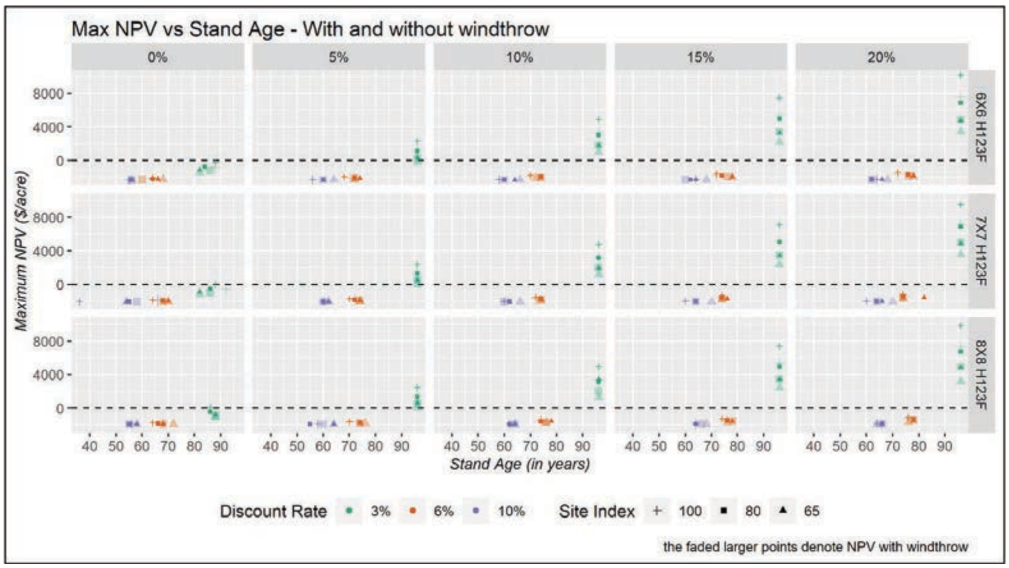


Figure1. The maximum Net Present Value (NPV) vs stand age with and without windthrows. Variables include plant spacing, discount rate, veneer %, and site index.

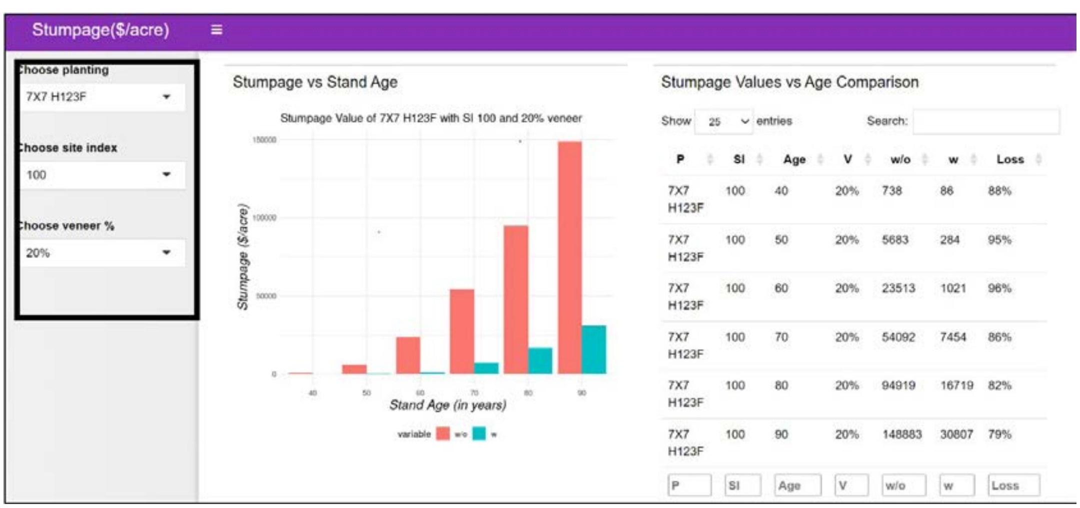


Figure 2. An interactive dashboard for determining profitability. Inputs include planting density, site index, and veneer % (the upper left corner). Outputs are summarized in graphical and tabular formats, with (in green) and without (red) windthrows.

PRECISE QUANTIFICATION OF FOREST DISTURBANCES WITH UAS

INVESTIGATORS

- **Joseph 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

The main goal of this research addressed how UAS can be properly utilized as an inventory mechanism prior to and after planned disturbance events. This was addressed through three primary objectives:

Objective 1. Develop standardized data collection methods with UAS platforms prior to and after planned disturbance events, such as timber harvest and controlled burns. This data collection will occur over several timber stands over a three-year period resulting in a robust data set for further analysis.

Objective 2. 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.

Objective 3. 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.

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). Two graduate students were funded through this HTIRC funding. Zach Miller successfully completed and defended his master's thesis on the topic. Out of this thesis, he and a group of co-authors have successfully published in the Journal of Forestry, and within Drones Journal. Cameron Miller also engaged in one year of data collection related to the funding.
- Despite the difficulties presented by the COVID-19 outbreak, Zach Miller was able to work with another graduate student, Cameron Wingren, in the summer and fall of 2021 to transfer research methods and results information for a smooth transition. The intent was for Cameron to focus more on the temporal recovery component and explore data collection with LiDAR on the UAS. In early fall 2022, however, Cameron was hired as UAS coordinator for the digital forestry initiative and is now funded by that. Cameron is still engaged in data collection prior to and after disturbance events but is not pursuing the research under a thesis option.
- Flights over controlled burn disturbances on Purdue properties were performed during spring, summer, and fall of 2020 and 2021. 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 that led to adjustment to determine 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. Recent data collection efforts are currently focused on controlled burns at Martell Forest and Purdue Wildlife Area. Another area of focus is a data collection of flights over the PIs property in a Northern Mixed Forest of the Upper Peninsula of Michigan. Data was collected in fall 2021, again in spring 2022 in leaf off, then again for leaf on prior to timber harvest, and October 2022 just as the fall color transition was beginning.

OBJECTIVE 2

- Zach Miller was able to streamline processing and classification methods over a Purdue Wildlife Area (PWA) 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 (Figure 1) 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 upon 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 staff member Jarred Brooke 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.
- Joseph Hupy is currently working to bring in a PhD student interested in classification methods with disturbance datasets. The work demonstrated by the student shows promise. The student will be funded outside of the grant as a teaching assistant, and external funding will be pursued for the student to continue what was started with this research.

Figure 1. 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, the PI, Joseph Hupy, worked with 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 primarily worked with Pike Lumber over spring and summer 2020 and 2021 to where he was told of timber plots that were going to be harvested, the type of harvest to occur, and a projected timber harvest date. In keeping these lines of communication, Zach was able to capture 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 be conducting 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 cited by Pike Lumber.
- Relationships are forming with stakeholders in northern mixed forest to explore these methods outside of Temperate Deciduous Forests.

PRODUCTS

PUBLICATIONS

1. Miller, Z.; Hupy, J.; Hubbard, S.; Shao, G. (2022) Precise Quantification of Land Cover before and after Planned Disturbance Events with UAS-Derived Imagery. Drones 6, 52. https://doi.org/ 10.3390/drones6020052
2. Cromwell, C.; Giampaolo, J.; Hupy, J.; Miller, Z.; Chandrasekaran. A. (2021) A Systematic Review of Best Practices for UAS Data Collection in Forestry-Related Applications. *Forests*. 12(7):957. https://doi.org/10.3390/f12070957
3. Miller, Z., J.P. Hupy, A. Chandrasekaran, G.F. Shao, S. Fei. 2018. Application of Post-Processing Kinematic Methods with UAS Remote Sensing in Forest Ecosystems, *Journal of Forestry*.
4. Miller, Zachary. 2021. Quantification of Land Cover Surrounding Planned Disturbances using UAS Imagery. *M.S. Thesis, School of Aviation and Transportation Technology, Purdue University*

PRESENTATIONS

1. Hupy, J.P. (2022) Nature Conservancy and Purdue Extension UAS Workshop. UAS Sensor Data Collection Strategies. Wright Forestry Center.
2. Hupy, J.P., Wingren, C. (2022) Digital Forestry UAS Presentation. DNR Forestry Division Annual Meeting. Brown County State Park, IN.
3. Hupy, J.P. (2020, August). Precise quantification of forest disturbance with unmanned aerial systems. Oral Presentation. Ecological Society of America, Purdue University - School of Aviation and Transportation Technology, West Lafayette
4. Hupy, J.P. (2020, February). Utilizing Unmanned Aerial Systems and Geospatial Technology for Wildlife Conservation. Keynote/Plenary Address. Indiana Chapter of the Wildlife Society 2020 Spring Meeting, Purdue University - School of Aviation and Transportation Techno, West Lafayette, IN

ISSUES

1. 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. Before the COVID-19 lockdown, Zach Miller had already established several study sites with Pike Lumber and was able to further communicate via email and phone. The COVID-19 situation continues to present challenges 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 more engagement of undergraduate researchers.
2. 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 the 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.

FUTURE PLANS

- In his role as UAS coordinator, Cameron Wingren will continue to engage in data collection related to disturbance events that will be hosted on a web platform hosted by digital forestry funds.
- Future graduate students will be examining how the planned disturbances over both the burned and harvested area have responded to the events mainly through repeated flights over the same area.
- Future data sets will look to other forms of forest regarding species, age, and composition to move away from focus on Temperate Deciduous forests.
- 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.
- The 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

INVESTIGATORS

- **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,** *Associate Professor, Forestry and Natural Resources, Purdue University*
- **Matthew Ginzel,** *Professor, Entomology, Forestry and Natural Resources, Purdue University*
- **Mark Coggeshall,** *Adjunct Assistant Professor, Forestry, University of Missouri*
- **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 Remote Sensing (RS) products with forest management scenarios. Specifically, we will focus on three areas of forest management: 1) tracking insect pest and pathogen incidence, severity, and spread, 2) early detection of drought stress-related symptoms, and 3) optimize RS acquisitions to determine the number of collections appropriate to make an informed management decision.

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 Missouri during 2020 and 2021, but plans were adjusted to meet the stated goals of this proposal. We found that remotely sensed hyperspectral data can discriminate American chestnut (Castanea dentata) 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 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 of manned (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 (Figure 1). The ability pf spectral data to classify blight, however, declines as additional classes of blight (e.g., none, mild, severe) are classified (Figures 2, 3) and classes become confused with each other (Figure 4).
- Spectral bands that are important for classification shift depending on collection period (Figure 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

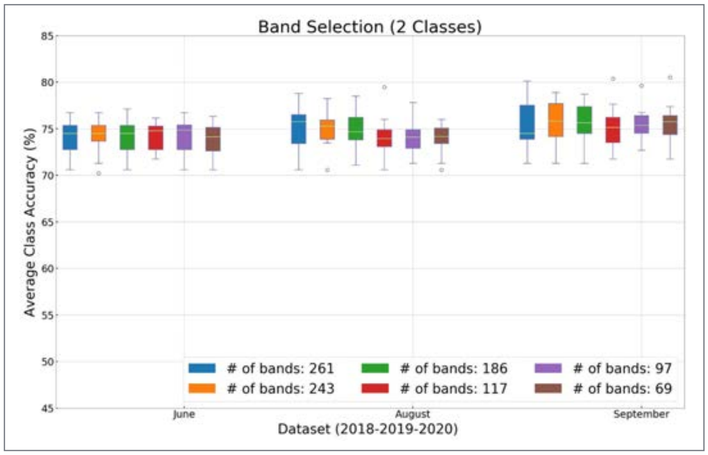


Figure 1. Classification accuracy of two-class (presence or absence) classification of chestnut blight in American chestnut trees using different spectral regions (visible and near infrared [VNIR]; shortwave infrared [SWIR]; and combined VNIR and SWIR). Classifications were made using support vector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

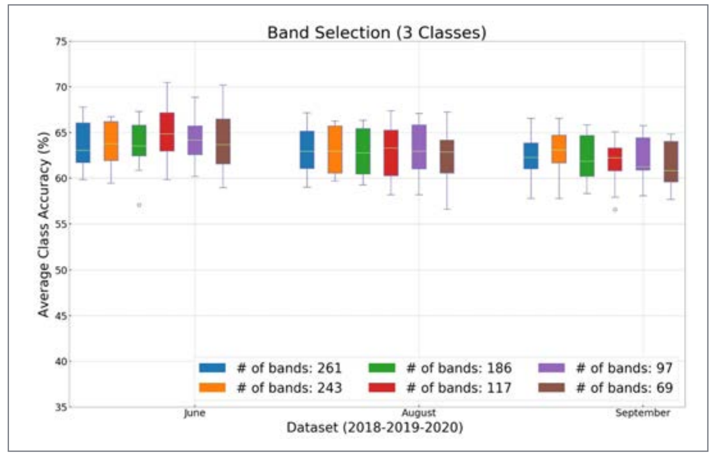


Figure 2. Classification accuracy of three-class (none, mild, or severe) classification of chestnut blight in American chestnut trees using different spectral regions (visible and near infrared [VNIR]; shortwave infrared [SWIR]; and combined VNIR and SWIR). Classifications were made using support vector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

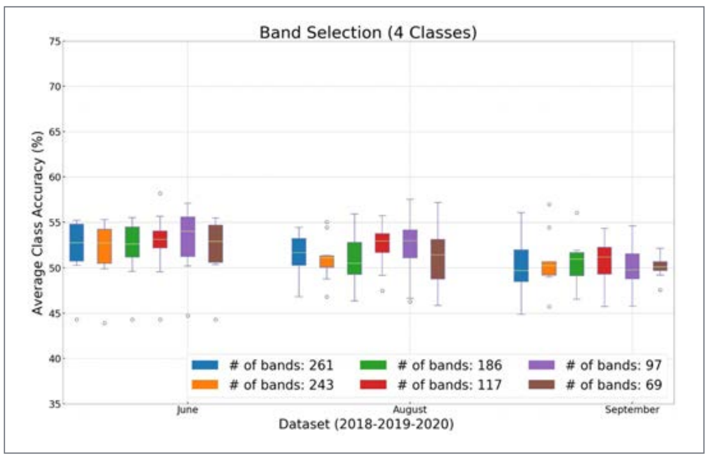


Figure 3. Classification accuracy of four-class (none, mild, moderate, or severe) classification of chestnut blight in American chestnut trees using different spectral regions (visible and near infrared [VNIR]; shortwave infrared [SWIR]; and combined VNIR and SWIR).

FUTURE PLANS

- Manuscript in preparation for spring 2023
- Manned aircraft data are being examined and related with UAV imagery to understand scalability of approach

PARTNERS/COLLABORATORS

- University of Wisconsin-Madison

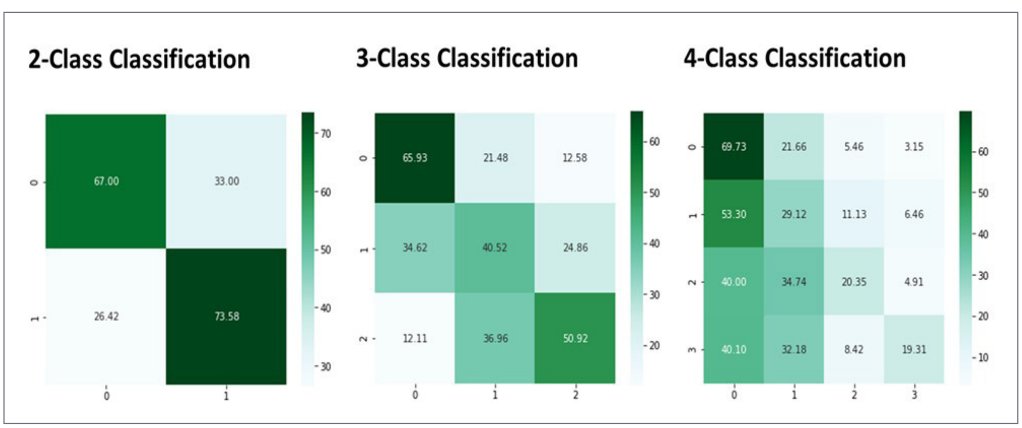


Figure 4. Confusion matrix based on classification. In the far-left panel, a 0 (no blight) is accurately classified 67% of the time and misclassified as having blight 33% of the time. Notice that as classes are added more classes are confused.

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

INVESTIGATORS

- **Guofan Shao,** *Professor, Forestry and Natural Resources, Purdue University (shao@purdue.edu)*
- **Keith Woeste,** *Molecular Geneticist and 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 3D image of each stem in a plantation, and transfer the data to the existing HTIRC database.

PROJECT TIMELINE

Tasks	Pre-Year 1	Year 1	Year 2	Year 3
Measurement Algorithm Development				
Algorithm Real-Time Implementation				
Auto-Locating and Labeling Trees				
Integrating Tree Position and Measurements				
System Adjustment and Interface Design				
System Applications and Improvements				

APPROACH

Overall, our research is progressing well, and progress has been made as originally proposed.

1) The research team in year 3 includes
   a. Four research advisors: Guofan Shao, Keith Woeste, Yung-Hsiang Lu, and James Warren.
   b. Two graduate students: Aishwarya Chandrasekaran (FNR) and Bowen Li (FNR)
   c. Six undergraduates: Hoang Tran (ECE), Akshat Verma (ECE), Elbek Nazarov (ECE), Aidan Crowley (ME), Robert Stewart (ME), Maximilian Hess (CE).
   d. One high school student: Audrey Ward.
2) The students are divided into four topic areas: tree stem straightness and volume computation (Hoang, Akshat, Bowen), tree positioning (Elbek, Aksha), base station positioning (Maximilian, Audrey, Aish), and camera customization (Robert, Aidan).
3) The team met twice a week in the spring and once a week in the summer and fall. Each student gave a report or feedback on research he/she has been working on every week.
4) The project fund was used to pay for materials, undergraduate students on an hourly basis, and partial expenses of a master's student.

KEY FINDINGS

Each group has made progress in their research. The team has made the following achievements:

1) The team won second place for a poster titled "Tree Positioning and Localization" by Elbek Nazarov & Akshat Verma in the Purdue University 2022 fall undergraduate research expo event.
2) The team tested our camera system for measuring tree diameters at an operational scale. The test site was a forest plantation owned by ArborAmerica, which consisted of ~6000 hardwood trees (mostly oak) and was spaced in ~100 rows. The camera system was mounted on a 4X4 truck. At an average speed of 5 mph, accurate tree DBHs were measured automatically.
3) The team developed an algorithm of tree stem straightness computation. A manuscript, titled "Measuring Tree Stem Diameters and Straightness with Depth-image Computer Vision," has been accepted by the *Journal of Forestry Research*.

FUTURE PLANS

The team will continue developing a customized camera system toward a prototype. The team will finish up the tree positioning system so that repeated tree measurements can be matched automatically. The team will test and improve the algorithm for natural hardwood forests.

PARTNERS/COLLABORATORS

- James Warren, Biological Scientist, 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

INVESTIGATORS

- **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 third year, during which we proposed to fulfill objectives #2 and #3.

Objective #2 – All of our work in Year 3 was focused on this objective, and while we are not completely satisfied with algorithm accuracy and precision, 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

During the previous two years, we: 1) established the image-processing pipeline that consists of edge image processing, finding pith and radius, detecting chain saw marks direction, and processing growth plot. We also developed software and user interface to assist in image analysis; 2) 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; 3) we annotated a sub; and 4) we developed an image segmentation-based method to identify rings when the surface is clean.

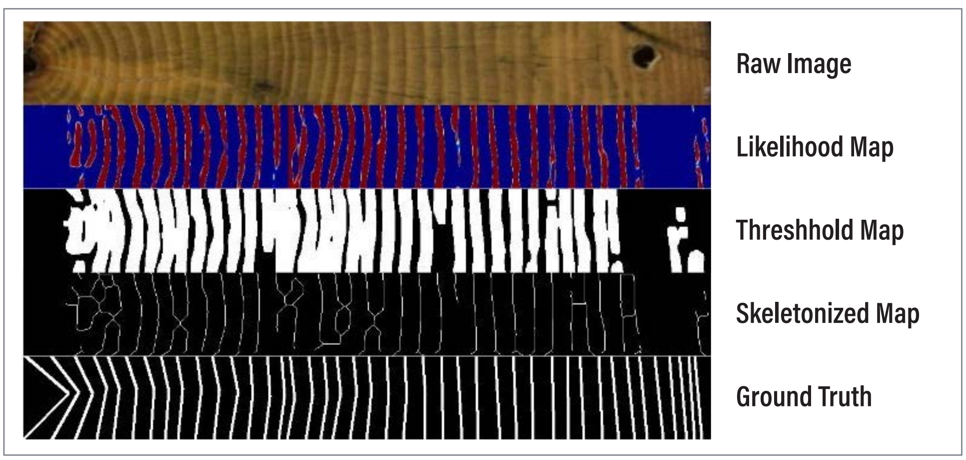


Figure 1. Sample growth ring extraction

Partial results of algorithm performance are in the table below:

Surface	AUC	F1
Rough	85.72%	0.5123
Clean Dry	79.14%	0.6096
Clean Wet	75.46%	0.7348

The table below displays the performance for several species. Overall, the Area Under Curve (AUC) values for all species varied from 0.8-0.9, indicating that the segmentation model could rate the probability of the pixel inside a single picture. Not all species perform equally when we evaluate performance under the growth ring level. In particular, black walnut (F1=0.6341) and soft maple (F1=0.6621) had the lowest F1 scores. This agrees with our intuition and expectations since during the annotating step these two species were the two most difficult species to manually determine the growth ring edges.

Our performance is a bit worse than some published research on softwood species due to the more challenging task of studying (especially diffuse-porous) hardwood species. Hardwood species are anatomically complicated in the cross-section and much harder to detect than the growth rings of softwood species. Furthermore, the average distance between two growth rings has a significant impact on performance.

Species	**Common name**	**AUC**	**PREC**	**REC**	**F1**
Fraxinus spp.	Ash	88.52%	0.8052	0.8878	0.8402
Tilia americana	Basswood	84.21%	0.7181	0.7964	0.7465
Juglans nigra	Black walnut	84.05%	0.5921	0.7067	0.6341
Prunus serotina	Cherry	85.92%	0.7011	0.7831	0.7338
Celtis occidentalis	Hackberry	82.80%	0.6998	0.8684	0.7714
Acer saccharum	Hard maple	85.81%	0.6143	0.8743	0.7176
Carya spp.	Hickory	86.70%	0.6744	0.8828	0.7614
Quercus rubra	Red oak	88.14%	0.6497	0.9163	0.7563
Acer saccharinum	Soft maple	84.09%	0.5435	0.8534	0.6621
Quercus spp.	White oak	87.19%	0.6838	0.9097	0.7749
Liriodendron tulipifera	Yellow poplar	85.13%	0.5694	0.9012	0.6958

Article in review:

Wu, F., Huang, Y., Benes, B., Warner, C., and R. Gazo. 2022. Data Collection and Deep Learning-Based Detection of Wood Growth Rings. *Information Processing in Agriculture*.

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.

LIST OF PARTNERS/STAKEHOLDERS/COLLABORATORS

- Pike Lumber Company, Akron, IN – industrial partner

BACKPACK SYSTEM FOR HIGH RESOLUTION FOREST INVENTORY

INVESTIGATORS

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

PROJECT OBJECTIVES

This proposal directly addresses HTIRC Organizational Objective 4: Develop digital forestry technologies.

Tools developed in this project will be essential for 2021 RFP particular interest area 1 and to address HTIRC Strategic Goals 1 and 2: Quantifying genetic gains and trait correlation estimates of trees currently in our tree improvement programs.

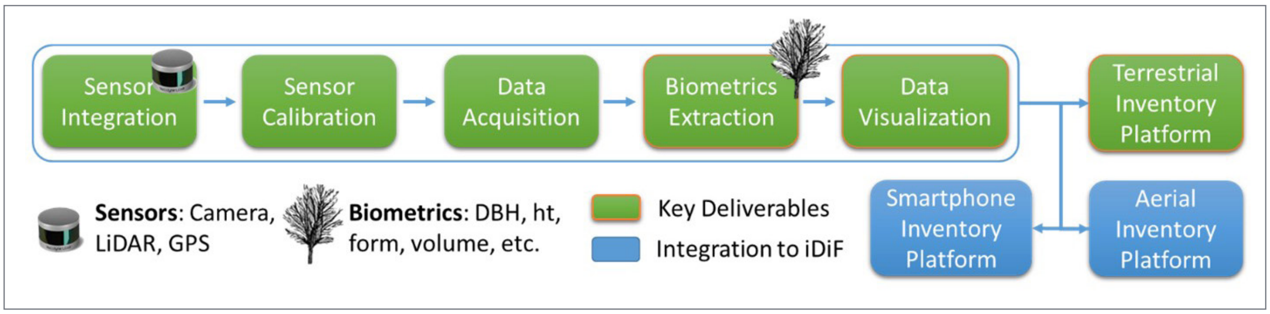


Figure 1.

APPROACH AND FINDINGS

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

- To date, the research team has developed four backpack LiDAR systems.
  a. First system is equipped with a Sony α7RII digital camera, NovAtel SPAN-CPT position and orientation system, and Velodyne VLP-16 Hi-Res LiDAR unit (Figure 2 – far left)
  b. Second system is equipped with an Ouster OS0 32 LiDAR unit and NovAtel PwrPak E1 position and orientation system (Figure 2 – middle left)
  c. Third system is equipped with a Velodyne VLP-16 LiDAR unit and NovAtel PwrPak E2 position and orientation system (Figure 2 – middle right)
  d. Fourth system is equipped with a Velodyne HDL 32E LiDAR unit and NovAtel PwrPak E2 position and orientation system (Figure 2 – far 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 and ArborAmerica 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.

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 5 cm (Figure 3). At this stage, the used procedure has been implemented for forest plantations.

Figure 2. Prototypes for the four different backpack systems equipped with VLP 16 High-Res (left), Ouster (middle left), VLP 16 (middle right), and HDL 32E (right) LiDAR units.

- The developed methodology in the previous step has been expanded to handle collected data in a natural forest. More specifically, a LiDAR-based Simultaneous Localization and Mapping (SLAM) strategy has been proposed by first conducting an odometry step to derive initial estimates of translation and rotation components between two successive LiDAR frames. In the odometry step, ground patches and tree trunks are extracted/matched between successive frames. Then, a mapping step is developed to estimate the trajectory of the Backpack system in a unified mapping coordinate system. GNSS/INS trajectory and/or UAV LiDAR data can be used to improve the Backpack trajectory.
- 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. Above ground point clouds are then used for the individual tree detection and localization, tree height estimation, and DBH evaluation. Experimental results from plantations and natural forests are quite promising.

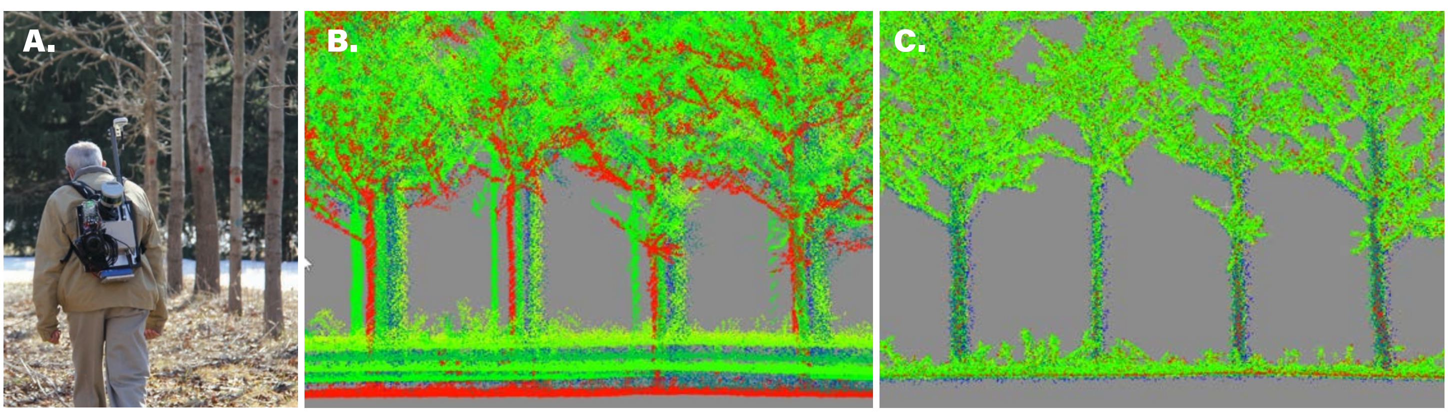


Figure 3. Backpack deployment in Martell Forest (a), and LiDAR point clouds before (b) and after (c) trajectory enhancement.

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; Morton Arboretum; Indiana Hardwood Lumbermen's Association; DNR Division of Forestry – Continuing Education Program; meeting with Amazon (AWS) on December 15, 2022). Moreover, we have several journal papers that have been published (see reference list). 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 provide high resolution point cloud for Martell Forest in September (leaf-on – September, 2021 and Leaf-off – December, 2021) (Figure 4). Another dataset will be solicited in early 2023.

PRODUCTS

PUBLICATIONS

Zhou, T.; dos Santos, R.C.; Liu, J.; Lin, Y.C.; Fei, W.C.; Fei, S.; and Habib, A., 2022. Comparative Evaluation of a Newly Developed Trunk-Based Tree Detection/Localization Strategy on Leaf-Off LiDAR Point Clouds with Varying Characteristics. *Remote Sensing* 14, no. 15: 3738. https://doi.org/10.3390/rs14153738.

Lin, Y.C., Shao, J., Shin, S.-Y., Saka, Z., Joseph, M., Manish, R., Fei, S., Habib, A., 2022. Comparative Analysis of Multi-Platform, Multi-Resolution, Multi-Temporal LiDAR Data for Forest Inventory. *Remote Sensing*, 2022, 14, 649. https://doi.org/10.3390/rs14030649.

Zhou, T.; Fei, S.; and Habib., A.; 2022. Forest Feature-based LiDAR SLAM (F2-SLAM) for Backpack Systems. Manuscript is finalized for submission to the *Remote Sensing of Environment* Journal.

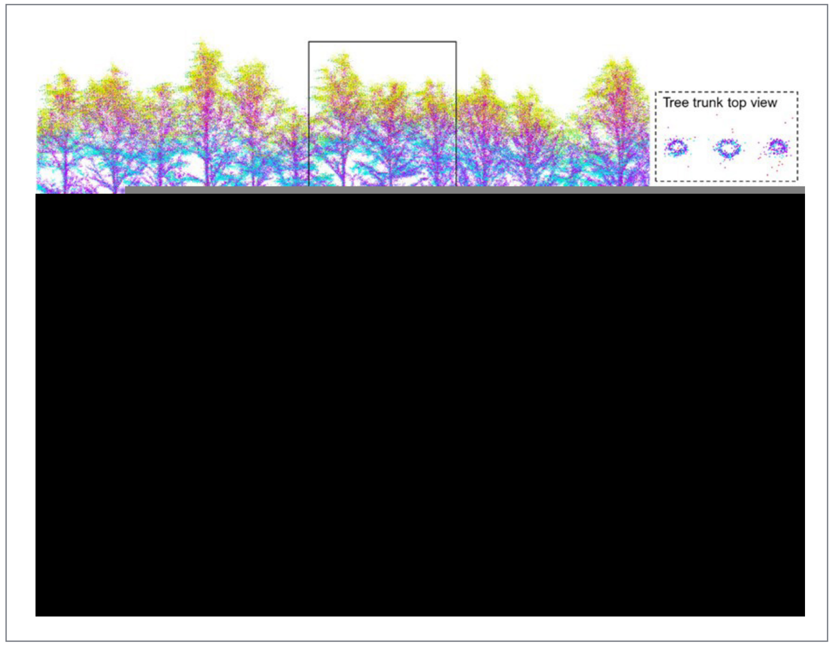


Figure 4. Cross-sectional profile of point clouds over Martell Forest from the statewide, VeriDaas Giger mode, UAV, and Backpack LiDAR systems.

PRESENTATIONS

Invited

Mobile Mapping in GNSS-challenging Environments: Digital Forestry and Smart Agriculture. Yonsei University, South Korea; December 15, 2022.

Mobile LiDAR for High Resolution Forest Inventory. Digital Forestry Retreat and Grand Opening, Wright Center, Martell Forest, West Lafayette, IN, August 8, 2022

Mobile LiDAR for Forest Inventory. DNR Division of Forestry, Continuing Education Program, February 24, 2022.

Contributed

Demonstration of the Backpack LiDAR System. AWS Meeting, John F. Wright Forestry Center, December 15, 2022.

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

INVESTIGATORS

- **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, with three main objectives. 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 (Figure 2) that best explain relative long-term success or failure of underplanting and enrichment plantings.

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).

EVALUATE CROP TREE RESPONSES TO RELEASE TREATMENTS

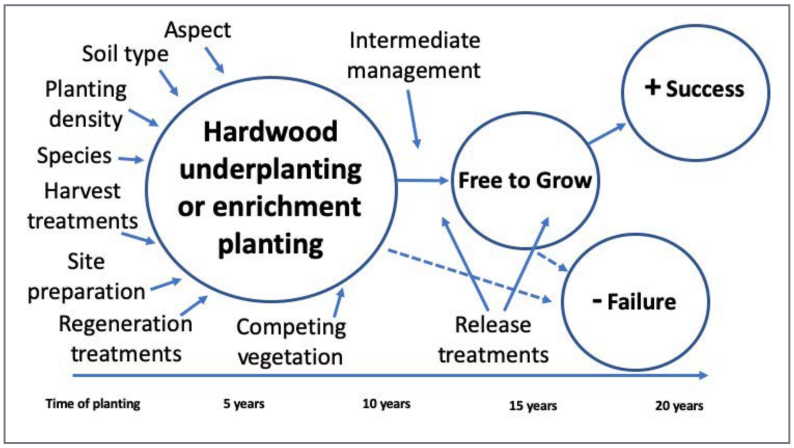


Figure 2. Example of factors that may help to explain relative success of underplanting and enrichment plantings.

- We have identified a subset of trials that are at the appropriate developmental stage (9-21 years old) and have sufficient stocking of dominant or co-dominant future crop trees to examine response to release from competition. The stands identified are 2001 and 2010 Nelson-Stokes and one of the 2013 SEPAC trials, because they have sufficient quantities of dominant and co-dominant trees and now require release in order to sustain their growth trajectories.
- To accomplish the release treatments, we used a split-plot design where half of the co-dominant and dominant trees in each replicate plot was randomly allocated to receive release or else designated as a control (no release). Release treatments consisted of a (3- or 4-sided) crown release (Figure 3), which is appropriate for this developmental stage. We avoided 4-sided crown releases on trees that neighbored other good crop trees. Trees that are not in a competitive (dominant and co-dominant) position were excluded, because they are unlikely to respond.
- In addition to release of our planted trees, at SEPAC we identified natural regeneration (60 stump sprouts and 60 seeded trees) of oak trees in a similar age class and competitive position on transects in the same stand as our other plots and also released these trees, which will further allow for comparison of responses to release for planted trees vs. natural regeneration.
- To quantify response to release, all experimental trees were measured for height and DBH, as well as canopy volume (as a function of crown height and crown diameter) at time of release and will be measured after each of the next two growing seasons.

Figure 3. View from above of a white oak (left) and northern red oak (right) after three-sided release at SEPAC in July 2022. Circle denotes position of released tree.

KEY 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 of intermediate or above.
- At Block C1 at the SEPAC Biomass planting (Figure 4), 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, 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.

- At the Nelson Stokes 2010 TNC planting in the unfenced midstory removal, overall survival was 48% after 12 years. For northern red oaks, average diameter was 15.6 mm, average height was 287 cm, and 38% of the survivors had a crown class intermediate or above.

For white oaks, average diameter was 12.3 mm, average height was 193 cm, and 26% of the survivors had a crown class intermediate or above. In the unfenced and crown thinned treatment, overall survival was 29% after 12 years. For northern red oaks, average diameter was 24.1 mm, average height was 424 cm, and 45% of the survivors had a crown class intermediate or above. For white oaks, average diameter was 15.2 mm, average height was 250 cm, and 33% of the survivors had a crown class intermediate or above.

In the fenced and crown thinned treatment, overall survival was 45% after 12 years. For northern red oaks, average diameter was 22.4 mm, average height was 408 cm, and 62% of the survivors had a crown class intermediate or above. For white oaks, average diameter was 14.5 mm, average height was 288 cm, and 30% of the survivors had a crown class intermediate or above.

In the fenced midstory removal, overall survival was 35% after 12 years. For northern red oaks, average diameter was 15.6 mm, average height was 262 cm, and 40% of the survivors had a crown class intermediate or above. For white oaks, average diameter was 12.2 mm, average height was 178 cm, and 6% of the survivors had a crown class intermediate or above.

Figure 4. Aerial views of the unfenced (left) and fenced (right) plots at the C1 block of the 2013 SEPAC Biomass Planting.

FUTURE PLANS

- Finish measurements on competitor trees.
- Measure responses to release treatments.
- Hold an Extension field day highlighting this project 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

INVESTIGATORS

- **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 Warren,** *Biological Scientist, USDA Forest Service*

PROJECT OBJECTIVES

To achieve our overall objective of improved black walnut breeding at HTIRC, we propose two related objectives: (1) 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, and (2) 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 to the Indiana State Tree Nursery Seed Orchard and other seed orchards.

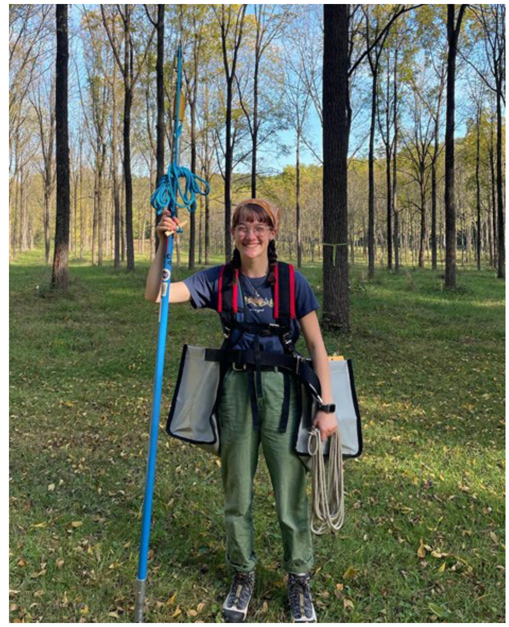
APPROACH

- Leaves or buds were sampled from plantation-grown trees (Figure 1)
- Diameter and form were rated at the time of sampling (Figure 2)
- DNA was extracted by a commercial lab
- SNP panel was identified by co-PI Cronn based on range-wide sample of black walnut
- SNP genotyping by Mass-array is underway; first results expected in January 2023.

Figure 1. Genetic material collection in a plantation.

Figure 2. Diameter and stem form are determined during data collection.

KEY FINDINGS AND ACCOMPLISHMENTS



The past year we collected DNA from the parents and offspring in the walnut breeding program. All the parents have been collected. Of about 78 families that we hoped to sample 25 offspring from, we have completed sampling for 25 families, and their DNA is extracted and stored onto 96-well plates. We have collected at least 15 progeny from an additional 19 families; DNA extraction is proceeding. We determined that bud samples will work well for DNA extraction. 525 samples have been submitted for genotyping at 120 SNP loci. Diameter and form ratings were measured for each progeny. Samples were collected from six plantations.

- Sample collection and data management still underway. Five 96-well plates of DNA submitted for mass-array genotyping; analysis not yet begun.
- Buds provide DNA of sufficient quantity and quality that we can continue sample collection through winter 2023.
- Sampling provided an opportunity to evaluate future value of plantations for breeding and other research. Many black walnut plantations grew poorly or lack adequate documentation or maps. Sampling visits are used to validate maps where possible.
- Initial data pipeline from Songlin Fei's iDiF data repository into HTIRC database explored so that we can add height data from HTIRC plantations.

FUTURE PLANS

- Complete sampling and measurement in 2023.
- Continue analysis of SNPs and kinship begun in 2022 based on first five plates of samples.
- Set up analysis pipeline based on initial pool of data. Include Vikram Chhatre as consultant for analysis.
- Obtain height data from plantations using UAV where possible.

PARTNERS/COLLABORATORS

- Evonik Corporation, Shadeland, IN
- Forgey Family Farm, Mike Forgey
- Perry Seitzinger
- Laura Hauck, USDA-FS, Pacific Northwest Research Station
- Songlin Fei, Lenny Farlee and Caleb Kell, Purdue University
- Carrie Pike, Regeneration Specialist, USDA Forest Service, Northeastern Area State & Private Forestry

INTEGRATING MORPHOLOGY, GENOTYPE, AND CHEMOTYPE BASED METHODS TO SUPPORT HTIRC BUTTERNUT CONSERVATION AND RESISTANCE BREEDING EFFORTS

INVESTIGATORS

- **Douglass F. Jacobs,** *Fred M. van Eck Professor of Forest Biology, Forestry and Natural Resources, Purdue University (djacobs@purdue.edu)*
- **John Couture,** *Associate Professor, Entomology, Forestry and Natural Resources, Purdue University*
- **Aziz Ebrahami,** *Graduate Student, Forestry and Natural Resources, Purdue University*
- **Anna Conrad,** *Research Plant Pathologist, USDA Forest Service*
- **Keith Woeste,** *Molecular Geneticist and Project Leader, USDA Forest Service, Adjunct Assistant Professor, Forestry and Natural Resources, Purdue University*

PROJECT OBJECTIVES

We will take advantage of the network of existing butternut research plantings established over the past 20 years within the HTIRC tree improvement program. The HTIRC's butternut collection contains both Butternut Canker Disease (BCD) resistant selections and accessions from across butternut's natural range, some of which may no longer exist in natural populations due to BCD. The pedigrees and hybridity of this material has not been sufficiently characterized for its use in BCD resistance screening and butternut conservation. Our four main objectives are as follows:

1) Determine the pedigree of trees in HTIRC's butternut tree improvement collection.
2) Determine the relative accuracy of morphology, genotype, and chemotype methods.
3) Assess disease incidence and severity among genotypes in HTIRC's butternut tree improvement collection.
4) Determine potential for spectral-based data to assess disease incidence and severity.

ABSTRACT

Resistance to pest and disease threats may be obtained by hybridization between native species and their relatives. Butternut (*Juglans cinerea L.*) is a native hardwood tree species threatened by butternut canker disease (BCD). Hybrids between butternut and *Juglans ailantifolia* have resistance to BCD and form a key component of BCD resistance breeding programs, yet are difficult to distinguish from pure butternuts.

In this project, we will integrate across three methods (morphology, genotype, and chemotype) to determine the pedigree of ~1,500 trees of interest in HTIRC's BCD resistance breeding program (Objective 1). We will distinguish among butternut, *J. ailantifolia*, and their hybrids including % hybridity (i.e., F1, F2 hybrid, BC1), and confirm chloroplast identity. We will then determine the relative accuracy of these three methods (Objective 2). Additionally, we will assess incidence and severity of BCD and bunch disease among genotypes (Objective 3), and the potential for spectral-based (chemotype) data to detect disease incidence and severity (Objective 4).

Combined, these three approaches will allow us to fully characterize the pedigree and disease resistance of the germplasm in the HTIRC butternut breeding program. This will enable us to detect unique sources of genetic diversity for conservation, to select the most butternut-like disease-resistant hybrids, to prioritize candidate trees for disease resistance screening, and to identify optimal germplasm for both pure butternut and hybrid seed orchards to support restoration in planted and natural forests.

Project results will be disseminated via field days, Extension publications, and web resources. This project will provide the first known comparison among morphology, genotype, and chemotype methods in determining hybridity in naturally hybridizing populations of a forest tree species. An approach that integrates phenotypes using advances in genetics and digital forestry should be a powerful tool for butternut resistance breeding and also provide scalable, relevant methods for other species.

APPROACH

- Morphology – We will use the following morphological traits to distinguish pure butternut from hybrids, which have consistently served as the best attributes among those presented by Woeste et al. (2009): pith color, lenticel shape, twig color, bud shape, phenology (bud break/leaf senescence).
- Genotype – Some of the butternut trees in HTIRC's collection were genotyped previously using DNA-based microsatellite markers. The chloroplast DNA of a subset of the trees was also genotyped using CAPS markers. The prior, small-scale, microsatellite genotyping did not provide enough information to distinguish F2 hybrids, and CAPS marker data was not obtained on all trees. We propose to genotype trees with a genomic Single Nucleotide Polymorphism (SNP) panel using Agena Iplex Gold massArray technology. This genomic tool will provide an easy, cost-efficient and high throughput method for rapidly genotyping current accessions, support future putatively resistant selections, and act as a reference for which to compare the other two methods. For interspecific panel development, bioinformatic analysis of sequence data obtained from exome capture and Genotyping by Sequencing (GBS) have been initiated by collaborators at the Canadian Forest Service and will be used for SNP marker selection (40 SNPs). After selection, we will validate the interspecific panel using known butternut, Japanese walnut, and early generation hybrids. The interspecific panel is already supported and funded by our Canadian collaborators. A GBS sequencing approach with the potential to generate ~12,000-15,000 SNPs will also be pursued for the characterization of all trees of interest to the study. The sequence data generated will enable the team to explore the genome for high quality SNPs that could be linked to traits of interest and for fingerprinting accessions in support of tree breeding and conservation programs.
- Chemotype – Spectroscopy measures the reflectance, transmission, or absorption of light after it comes in contact with an object. The frequency of light can vary, and sensors are equipped to measure wavelengths within the visual or NIR range. Spectra, e.g., NIR spectra, are affected by the chemical and physical properties of an object (Cozzolino 2014), so each tree (and tree tissue) will have a unique spectrum ("chemotype"). The chemotype is a byproduct of a tree's genetic background and the environment in which it is growing, including its exposure to different stressors. For each tree used for genotyping (~1,500 across three sites in Table 1), spectra will be collected during the growing season at approximately the same time (and tree phenology stage) from 3-5 leaves at uniform locations, and spectra from each tree averaged. Leaf spectra and background measurements will be collected using a handheld NeoSpectra Scanner (SiWare Systems) according to the methods of Conrad et al. (2020). Additional spectral sensors, e.g., NIRvascan and SVC 1024 I, will be used to collect data as needed.

Table 1. The network of existing butternut research plantings >10 years old at Martell Forest within the HTIRC tree improvement program. Notes: number of trees at time of planting does not account for subsequent mortality; JC: butternut; JXC: hybrid butternut; JA: Japanese walnut.

Planting	Year of Origin	Species / genotypes	Number of trees	Number of accessions	Notes
BNUT2	2007	JC, JXC	595	136	Seedlings and grafts
BNUT3	2010	JC, JXC,	1456	267	Seedlings; *Sister planting at SEPAC with 686 trees
BNUT4	2011	JC, JA, JXC	1306	175	Seedlings; Trees planted over 3 years from 2011 to 2013

- The collection of the aforementioned data forming Objective 1 represents the core focus of this project proposal. Once this data set is complete, we will accomplish the data analysis in the remaining objectives in order to:
  - Determine the relative accuracy of morphology, genotype, and chemotype methods (Objectives 1 and 2).
  - Assess disease incidence and severity among butternut genotypes (Objective 3).
  - Determine potential for spectral-based data to estimate disease incidence and severity (Objective 4).

KEY FINDINGS AND ACCOMPLISHMENTS

- Butternut canker disease incidence, severity, and mortality have been recorded for each tree between 2020-2022 (Figure 1).
- Incidence of walnut witches' broom symptoms were recorded (Figure 1) and presence of phytoplasma pathogen was confirmed via molecular methods in summer 2022 (manuscript accepted with revisions in Plant Disease, Fearer and Conrad).
- Chemotypes were collected from a subset of trees for preliminary investigation in summer 2022.
- The leaves of 1,500 butternut trees were collected in summer 2022 and freeze-dried (Figure 2). The leaves will soon be processed for genomic analysis.
- A subset of samples (96 genotypes, butternut and hybrid) was collected, DNA extracted, and shared with Canadian collaborators to process MassArray validation.
- 500 individuals of butternut and hybrid are being processed to share with Canadian collaborators to analyze the hybridity of the HTIRC collection.
- Project updates were presented at the Northern Forest Genetics Association Biannual Meeting during summer 2022 in Delaware, OH.

Figure 1. Butternut research planting at Martell Forest. Butternut canker disease is evident on trees in this experimental site, while the tree in the foreground also has bunch disease.

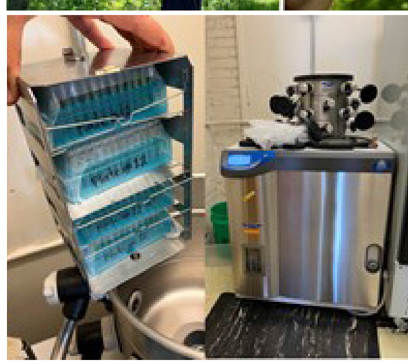


Figure 2: Collecting leaves in the field and processing them with a freeze drier in the lab.

FUTURE PLANS

- Chemotypes from all genotyped trees will be collected in summer 2023.
- Genotyping by Sequencing (GBS) of 1,500 individual trees will be processed.
- Genotype-phenotype association analysis will be conducted.

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Conrad, A.O., Li, W., Lee, D-Y., Wang, G-L., Rodriguez-Saona, L., and Bonello, P. (2020). Machine learning-based presymptomatic detection of rice shealth blight using spectral profiles. *Plant Phenomics* 2020:8954085.

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EFORESTER: AI-ASSISTED SMARTPHONE APP FOR AUTOMATED TREE INVENTORY

INVESTIGATORS

- **Song Zhang,** *Professor, Mechanical Engineering, Purdue University (zhan2053@purdue.edu)*
- **Songlin Fei,** *Professor, Forestry and Natural Resources, Purdue University*

PROJECT OBJECTIVES

1. Develop a device containing several RGB cameras and LiDAR cameras to reconstruct the accurate 3D geometry of target trees.
2. Measure the orientations, diameters and heights with contactless method.
3. Classify the sorts of trees based on the vein and size information.

ABSTRACT

Contactless tree size measurement and sort classification method is important to forestry management and valuation. In September 2022, Songlin Fei and Song Zhang hired a new PhD student, Wang Xiang, to take over the project from Fanyou Wu. The APP is under development and basic method is proposed. We first create the depth value for each of the pixels of RGB image from the LiDAR data through bilinear interpolation and then reconstruct 3D points of tree surfaces. With 3D point cloud data we can estimate the tangent vector and obtain the normal vector of each pixel to get the orientation of the trees. Since the LiDAR does not provide 3D points with high resolution nor high accuracy, we select a segment of the point cloud data and compute the average depth of these segment pixels as the distance from the trees to the camera. We then compute the diameter of the trees based on the geometric relationship and further construct the diameter error function to improve measurement accuracy by applying this error function.

Experimental results show that at distances from 0.5 m to 2 m with the largest elevation of 26 degrees, the proposed method can achieve 3 mm radius measurement accuracy for the cylinder surfaces with a radius of 40 mm and 70 mm, and 5 mm accuracy for the cylinder surface with a radius of 110 mm. Moreover, we plan to develop methods for tree height measurement and sort classification. 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.

APPROACH

1. LiDAR-based reconstruction: We reconstruct the 3D geometry of tree surface with an RGB image and LiDAR depth data by pinhole projection model.
2. Orientation determination: We estimate the orientation of tree by computing the tangent vectors and normal vectors via differential geometry on each point of the parameterized tree surface we reconstruct.
3. Diameter estimation: We select a segment of the point cloud data and compute the average depth of these segment pixels as the distance from the tree to the camera. We then compute the diameter from the geometric relationship of each point on the tree surface.
4. Results optimization: Apply our constructed error function of diameter estimation and then we can modify the average depth to improve the estimation results.

KEY FINDINGS AND ACCOMPLISHMENTS

1. For all size tree surfaces, ideal diameter error function shows a linearity on the capture distance when the capture distance is large enough (Figure 1).
2. We can capture the tree at several different distances and modify the average depth with a small factor to improve the estimation results based on the linearity of error function. In fact, the estimation achieves the optimal value once the data variance approach minimum (Figure 2).
3. We measured trees in Purdue Horticulture Park with both our method and a caliper, and the results are consistent. However, the accuracy of our method doesn't change as capture distance changing, since the

quality of RGB image would be higher but the accuracy of LiDAR data would be lower when capture distance become smaller (Figure 3, Figure 4).

4. Low resolution of LiDAR data may lose the information about the vein of tree surface in 3D geometry, but such smooth data help us estimate the diameter of a tree since we regard the tree surface as a cylinder surface (Figure 5).
5. Our work was submitted by SPIE Conference Defense + Commercial Sensing (DCS23) with paper number No.12524-8. The abstract was accepted by the conference, and an oral presentation will be given in May 2023.

FUTURE PLANS

1. Improve the diameter estimation by using more than one RGB camera to get higher-quality data.
2. Measure the heights of trees with same device.
3. Classify the sort of trees with higher-quality data, including more details about the vein of tree surfaces.

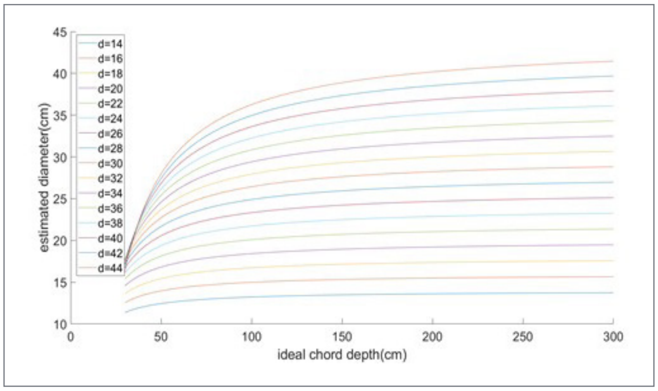

Figure 1. Examples of estimated diameter function with different capture distances and tree sizes. In fact, for large capture distance the estimated diameter function is approximately linear and monotone on both tree size and capture distance.

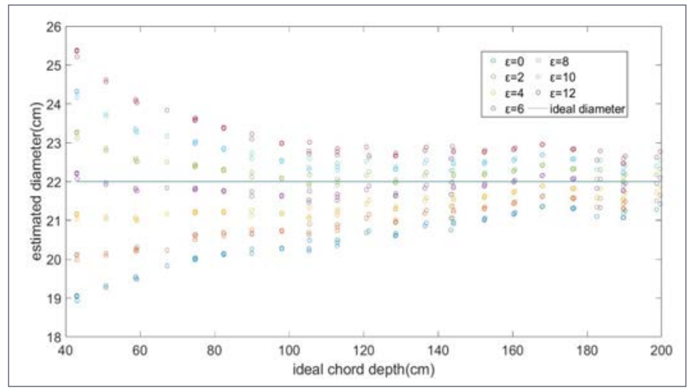

Figure 2. Diameter estimation optimization with different factor ε. The purple data point is with minimal variance in this image, which approach the ideal diameter best.

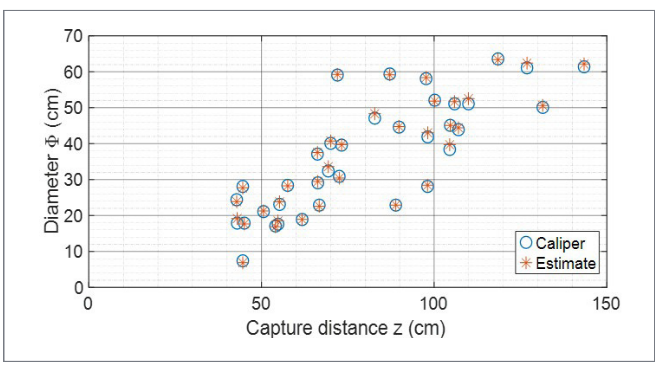

Figure 3. Tree diameters estimation results with our method and a caliper. We captured 3-5 images for each tree and the results are consistent.

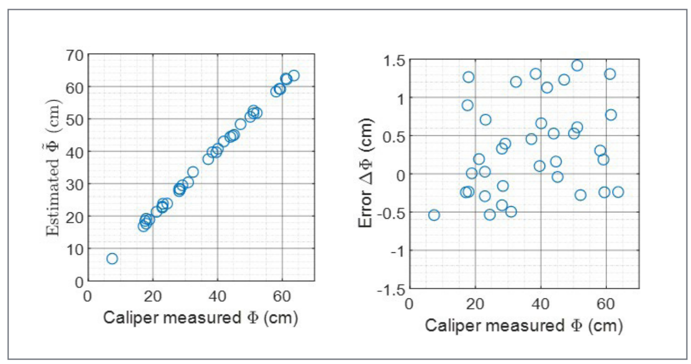

Figure 4. The behaviors of diameter estimation results and diameter error. The error is not notably influenced by capture distance.

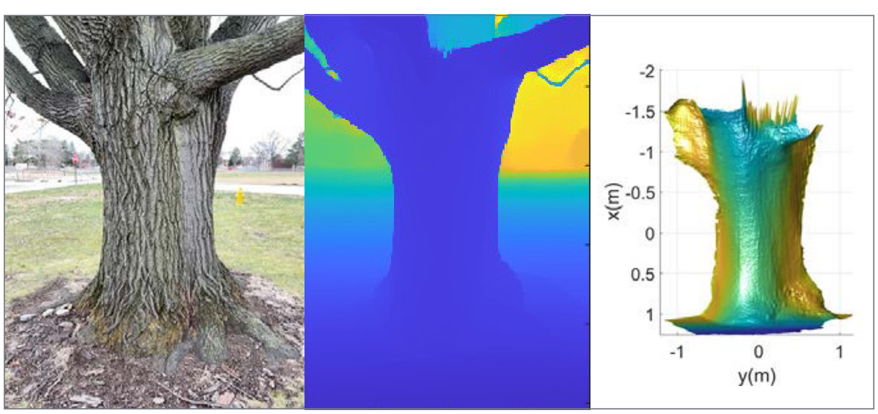

Figure 5. An example of tree reconstruction. Some vein information is missed in the 3D geometry. However, it makes the data smooth and is better for our diameter estimation.

CREATING A DIRECTORY, DEPOSITORY, AND DATABASE FOR HISTORICAL GENETIC AND TREE IMPROVEMENT TRIALS

INVESTIGATORS

- **Rebekah Shupe,** *Research Associate, Forestry and Natural Resources, Purdue University (rfshupe@purdue.edu)*
- **Songlin Fei,** *Professor, Forestry and Natural Resources, Purdue University*
- **Carolyn "Carrie" Pike***, Regeneration Specialist, USDA-FS, Eastern Region State, Private, and Tribal Forestry, Purdue University, West Lafayette*

PROJECT OBJECTIVES

- Preserving historical (pre-1980) documents and data from genetic and tree improvement trials in a digital format.
- Create a public directory, depository, and database of metadata and raw data of historical genetic and tree improvement trials.

ABSTRACT

Throughout the mid- to late 20th century, federal, state, and tribal governments 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 overcome challenges caused by the lack of seed availability, assisted migration of forests, and the decimation of forests due to pests. 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, and the HTIRC/Forest Service Plantings Database organized by James Warren to create a list of historical genetic tree plantings.
- Received data and information from the Tree Regeneration Center at Michigan State University, FERNOW Forest in Parsons, WV, Daniel Boone National Forest in Winchester, KY, and the OARDC at Ohio State University
- Verified the existence of plantings from the aforementioned 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, Cloquet Forestry Center in Cloquet, MN, Northern Research Station in Rhinelander, WI, and the Tree Regeneration Center at Michigan State University in East Lansing, MI, to digitally scan and physically collect the data of historical genetic tree plantings to digitize in an electronic format.
- Created a website for our directory, depository, and database for currently verified plantings and available data that can be accessed by interested researchers using Weebly and ESRI products.
- Generated a workflow for transcribing hard copies of data into a workable format that can be easily summarized using statistical programs.

KEY FINDINGS

- Using the above approach, the existence of 1,172 plantings has been confirmed throughout 18 states. Of the 1,172, a total of 466 plantings were verified to be active and alive plantings, 261 were verified to not be recoverable, 5 were verified to be abandoned but not removed (inactive), and 440 have been confirmed to be active but we are awaiting location information to verify.
- Out of the 1,172 plantings that have been confirmed, only 416 have an accompanying dataset. Some of the data that are available are very limited, but about 16% do include extensive data measurements and accompanying documents.
- Have digitized about 5% of collected data into a workable format for statistical programs.

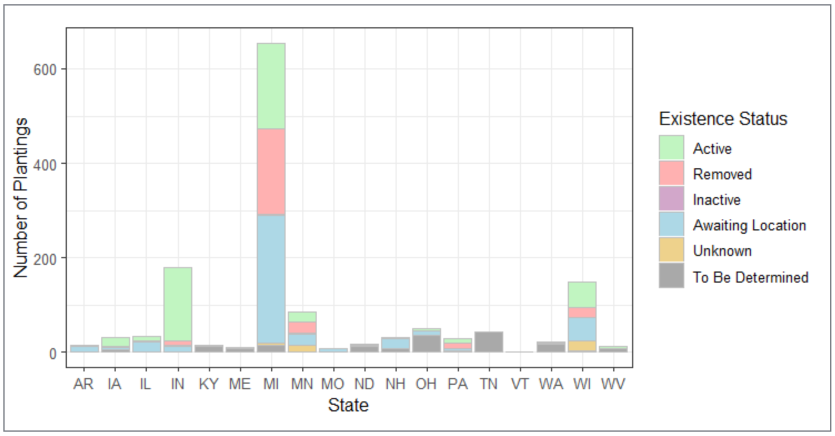

Figure 1. Genetic and tree improvement trials across 18 U.S. states and the count of active plantings (green), removed or dead plantings (red), alive but inactive plantings (violet), plantings without location data (blue), unknown plantings with no information to be found (yellow), and plantings yet to be verified (gray).

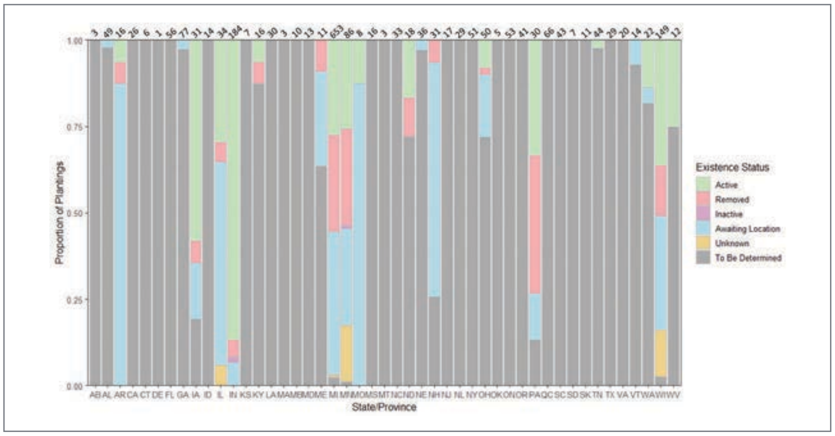

Figure 2. Genetic and tree improvement trials across 41 U.S. states and six Canadian provinces and the proportion of active plantings (green), removed or dead plantings (red), alive but inactive plantings (violet), plantings without location data (blue), unknown plantings with no information to be found (yellow), and plantings yet to be verified (gray) with the count totals at the top of the figure.

PARTNERS/COLLABORATORS

- USDA Forest Service

COLLABORATORS

- James Warren, Yue "Shirley" Li, Sungchan Oh, Nicholas Labonte, Paul Bloese, Ron Zalesny, Andrew David, Gwen Short, Brian Beheler, 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.

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

For the latest HTIRC news, check out these resources on the HTIRC website:

- E-newsletters, 677 subscribers. https://htirc.org/resources/newsletters/
- News archive https://htirc.org/news/news-archive/
- Annual reports https://htirc.org/annual-report/

EXTENSION PRODUCTS

In 2022 we produced or updated a variety of online resources, including videos on hardwood management, invasive species, and tree identification These are posted at https://htirc.org/resources/landowner-information/ and https://www.purdue.edu/fnr/extension/ and include:

- ID That Tree series: Over 90 videos highlighting native and invasive trees and shrubs; 8,229 views in 2022. https://youtube.com/playlist?list=PLgoGnq-fak7V9w3jf2Sj_6-pNaw4sX4Ga.
- Woodland Management Moment series: This series covers various woodland management topics in short video messages to landowners; 1,829 views in 2022. https://youtube.com/playlist?list=PLgoGnq-fak7VTTnF4Bh9HvQnB_azYbAfY
- Woodland Stewardship for Landowners video series: Videos from this collaborative 10-video series between Purdue FNR and the Indiana Department of Natural Resources address management issues relevant to woodland owners; 3,905 views in 2 years. https://youtube.com/playlist?list=PLgoGnq-fak7XgiEFkpuQNAFa0rM4elCis.
- 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.
- Recently posted: Conservation Tree Planting Webinar covering the steps to success for conservation tree plantings. https://www.youtube.com/watch?v=6IJ0olgMAW8.
- Dr. Songlin Fei, in collaboration with several partners, launched the Alien Forest Pest Explorer interactive web tool. https://mapsweb.lib.purdue.edu/AFPE/.
- The Digital Forestry Initiative has a data portal providing access to existing and new remote sensing data. https://lidar.digitalforestry.org/.
- Webinar on Tree-of-Heaven Identification and Management with EAB University; 280 views in 2022. https://www.youtube.com/watch?v=dBr_F2HEbw4.
- Dr. Mo Zhou has developed a website with hardwood timber price trends for Indiana at www.foresteconomics.info.

New Publications coming in 2023:

- Understanding White-Tailed Deer and Their Impact on Indiana Woodlands
- Managing White-Tailed Deer Impacts on Indiana Woodlands – Publications in a series from the Deer Impact Toolbox, which is part of the Integrated Deer Management Project at Purdue University.

PROGRAMS

- These programs shared the latest HTIRC information to landowners and/or natural resources professionals in a mix of online and in-person formats:
- Landowner's Conservation Tree Planting Workshops
- Forest Management for the Private Woodland Owner courses
- Walnut Council Field Days
- Forest Pesticide Applicators Continuing Education Program
- Tree Farm/IFWOA Landowners Field Days

- Timber Sales 101 workshop
- Invasive Species field days and presentations
- Presentations at the Walnut Council annual meeting
- Presentation for Illinois Beginning Forest Landowners education program
- Presentations at Green Industry continuing education programs
- Hoosier Hardwood Festival education programs

We actively engage with our partners and many other groups, agencies and organizations with similar goals and interests to understand management and information needs and facilitate distribution of research-based tree and forest management information to appropriate audiences.

EDUCATION

Developing future researchers and practitioners with expertise in the science and application of tree improvement, management and protection of hardwood forests is fundamental to the HTIRC. This year, through our project-based funding model, we supported nine MS students, nine PhD students, five postdocs, six undergraduate research technicians and one high school student over the summer.

HTIRC STUDENTS WHO GRADUATED IN 2022

***Aziz Ebrahimi** (Tehran, Iran), PhD Dissertation: "Morpho-Physiological & Genomics Analyses Underlying Adaptations of Hardwood Trees to Abiotic Stressors." Current position: Postdoc at Purdue University (FNR)*

***Sarah Rademacher** (Minneapolis, MN). MS thesis: "Understory response to shelterwood and burn treatments in a dry Quercus forest in Indiana."*

2022 OPERATIONAL TREE IMPROVEMENT REPORT

The HTIRC's tree improvement program seeks to improve the genetic quality of seed provided to nurseries in Indiana and across the Central Hardwood Forest region. Improved breeding populations of black walnut, black cherry, red oak and white oak are selected for superior timber quality characteristics. The HTIRC is also developing populations of American chestnut and butternut with enhanced disease resistance to chestnut blight and butternut canker respectively.

BREEDING PROGRESS BY SPECIES

BLACK WALNUT

The HTIRC is continuing its long-running black walnut breeding program, with two second-generation progeny tests ready for planting in 2023. The HTIRC began making second-generation selections out of its black walnut tests in 2011 (Figure 1), but the emergence of thousand cankers disease (TCD) halted the selection process in 2014. Many feared that TCD would spread and begin killing black walnuts en masse, which would necessitate starting a resistance breeding program for black walnut. Fortunately, TCD's threat to black walnut in the eastern United States is far less than initially projected. With the threat of TCD now thoroughly understood, the HTIRC is resuming its second-generation selection program, reinforcing its commitment to providing improved genetics to nurseries and landowners.

WHITE OAK

The grafted white oak orchard at Lugar Farm had a mast year in 2022, producing more seed than the HTIRC staff could collect. Over 20 families were harvested and sown at the Indiana DNR Vallonia State Nursery. Bark grafts performed in 2019 at the Lugar and Martell white oak orchards continue to mature, with two bark grafted families producing sufficient seed to test this year (Figure 2, left). Sixteen grafted white oaks were provided to

Figure 1. Two second-generation black walnut selections made in 2013.

Figure 2. Left: Mature 2019 white oak bark grafts at Martell Forest. Right: A plus-tree oak selection made at Nelson-Stokes.

the Indiana Division of Forestry to establish a new grafted white oak orchard at Vallonia.

White oak grafts from 2021 were planted at the Lugar white oak orchard to expand the number of families and increase future seed production. A future clone bank site was established at the Lugar Germplasm Block. Planted with 1-0 white oak seedlings, this site will be used as a white oak germplasm repository and to educate future HTIRC students and staff on field grafting techniques.

Efforts to expand the HTIRC's white oak germplasm collection continues, with new plus-tree selections made at Purdue's Nelson-Stokes property (Figure 2, right) and other private locations in northern Indiana. Throughout the next five years the HTIRC plans to expand its white oak collection from 60 accessions to 200. This ensures that the white oak improvement program has an adequately diverse genetic base for multiple generations of selection.

Figure 3. 2023 was a bumper crop for butternut, with the Martell Germplasm block being especially productive.

Figure 4. A new hybrid butternut tree added to the HTIRC's collection, boasting a 55" diameter and a 95' crown spread.

BUTTERNUT

Since 2003, the HTIRC has planted butternut seedlings into screening blocks for challenging pure and hybrid butternut seedlings with the deadly butternut canker disease (BCD). As these plantings mature, trees with enhanced resistance to BCD are selected and grafted into second-generation breeding orchards. In 2022, 17 new BCD-resistant selections were grafted for planting into the Lugar second-generation breeding orchard, with substantially higher grafting success than 2021. Eighteen resistant butternut grafts were provided to the Indiana Division of Forestry to expand its hybrid butternut seed orchard at Vallonia State Nursery. Additional wild hybrid germplasm was collected to further increase the diversity of the HTIRC's butternut collection (Figure 4).

2022 was a mast year for butternut. Nearly 12,000 nuts were harvested from 125 trees, mostly from the Martell germplasm block, which contains many untested families. Seed from 75 families was sown for a new screening block to be planted in 2024. This screening block and the 2021 Martell Butternut 5 screening block will ensure a steady supply of new resistant butternut selections through the 2030s.

Figure 5. Left: Newly sown American chestnut transgenic seed at Martell Forest. Right: An additional American chestnut found at Ligonier City Park, IN.

AMERICAN CHESTNUT

The HTIRC's grafted American chestnut collection is an invaluable resource, allowing a very diverse population of American chestnuts to be crossed at a single location. Unrivaled by other members and state chapters of the American Chestnut Foundation, the American chestnut grafting program is a distinct strength of the HTIRC. In 2022, 20 new American chestnut families were successfully grafted, and the Lugar grafted orchard was expanded with grafts made in 2021. Once the 2022 grafts are planted, the Lugar grafted orchard will boast 50 unique families for crossing. Last fall, 3,000 American chestnut seeds were collected for production of rootstocks and distribution for conservation plantings.

The HTIRC has collaborated with the American Chestnut Foundation, the University of New England and SUNY since 2019 in crossing wild-type American chestnuts with transgenic (TG) pollen containing the Oxalic Acid Oxalase (OxO) gene to confer resistance to the chestnut blight pathogen. The HTIRC crossed trees in the Duke orchard with TG pollen in 2019, 2020 and 2021. Transgenic seedlings from the 2020 crossing season were outplanted adjacent to the Duke American chestnut orchard. Arranged for disease resistance screening, these seedlings will be inoculated in fall 2023 with chestnut blight. Transgenic seedlings from the 2019 crossing season were inoculated in summer 2022, and infection response was rated last December. Ten seedlings from eight crosses showed outstanding resistance to chestnut blight as well as growth comparable to wild-type control trees. These 10 seedlings were selected for repropagation, and will be grafted this spring for bulk production of transgenic pollen.

At the time of publication, deregulation of the transgenic American chestnut by the USDA remains a possibility. If the transgenic American chestnut is deregulated for release to the wild, the HTIRC is prepared to be a major force for restoration of the American chestnut to the forests of Indiana and beyond.

2022 RESEARCH PUBLICATIONS

- HTIRC-related research papers published in 2022 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/
- Carpenter, J., Jung, J., Oh, S., Hardiman, B., Fei, S. An Unsupervised Canopy-to-Root Pathing (UCRP) Tree Segmentation Algorithm for Automatic Forest Mapping. *Remote Sensing*. 2022, 14, 4274. https://doi.org/10.3390/rs14174274
- Carpenter, J. et al. 2022. An Unsupervised Canopy-to-Root Pathing (UCRP) Tree Segmentation Algorithm for Automatic Forest Mapping. *Remote Sensing*. 14(17), 4274.
- Chandrasekaran, A. et al. 2022. Automated inventory of broadleaf tree plantations with UAS imagery. *Remote Sensing* 14(8), 1931.
- Lin, Y.C., Shao, J., Shin, S.-Y., Saka, Z., Joseph, M., Manish, R., Fei, S., Habib, A., 2022. Comparative Analysis of Multi-Platform, Multi-Resolution, Multi-Temporal LiDAR Data for Forest Inventory. *Remote Sensing.* 14, 649. https://doi.org/10.3390/rs14030649
- Miller, Z., Hupy, J., Hubbard, S., Shao, G. 2022. Precise Quantification of Land Cover before and after Planned Disturbance Events with UAS-Derived Imagery. *Drones.* 6, 52. https://doi.org/ 10.3390/drones6020052
- Montague, M.S., Landhäusser, S.M., McNickle, G.G., Jacobs, D.F. 2022. Preferential allocation of carbohydrate reserves belowground supports disturbance- based management of American chestnut (Castanea dentata). *Forest Ecology and Management.* 509:120078
- Oh, S. et al. 2022.Canopy height model generation and validation using USGS 3DEP LiDAR data in Indiana, USA. *Remote Sensing*. 14 (4), 935.
- Zhou, T., dos Santos, R. C., Liu, J., Lin, Y.C., Fei, W.C., Fei, S., and Habib, A., 2022. Comparative Evaluation of a Newly Developed Trunk-Based Tree Detection/Localization Strategy on Leaf-Off LiDAR Point Clouds with Varying Characteristics. *Remote Sensing.* 14, no. 15: 3738. https://doi.org/10.3390/rs14153738
- Zhou, T., Fei, S., and Habib., A. 2022. Forest Feature-based LiDAR SLAM (F2-SLAM) for Backpack Systems. Manuscript is finalized for submission to *Remote Sensing of Environment*.

NOTES

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HARDWOOD TREE IMPROVEMENT
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