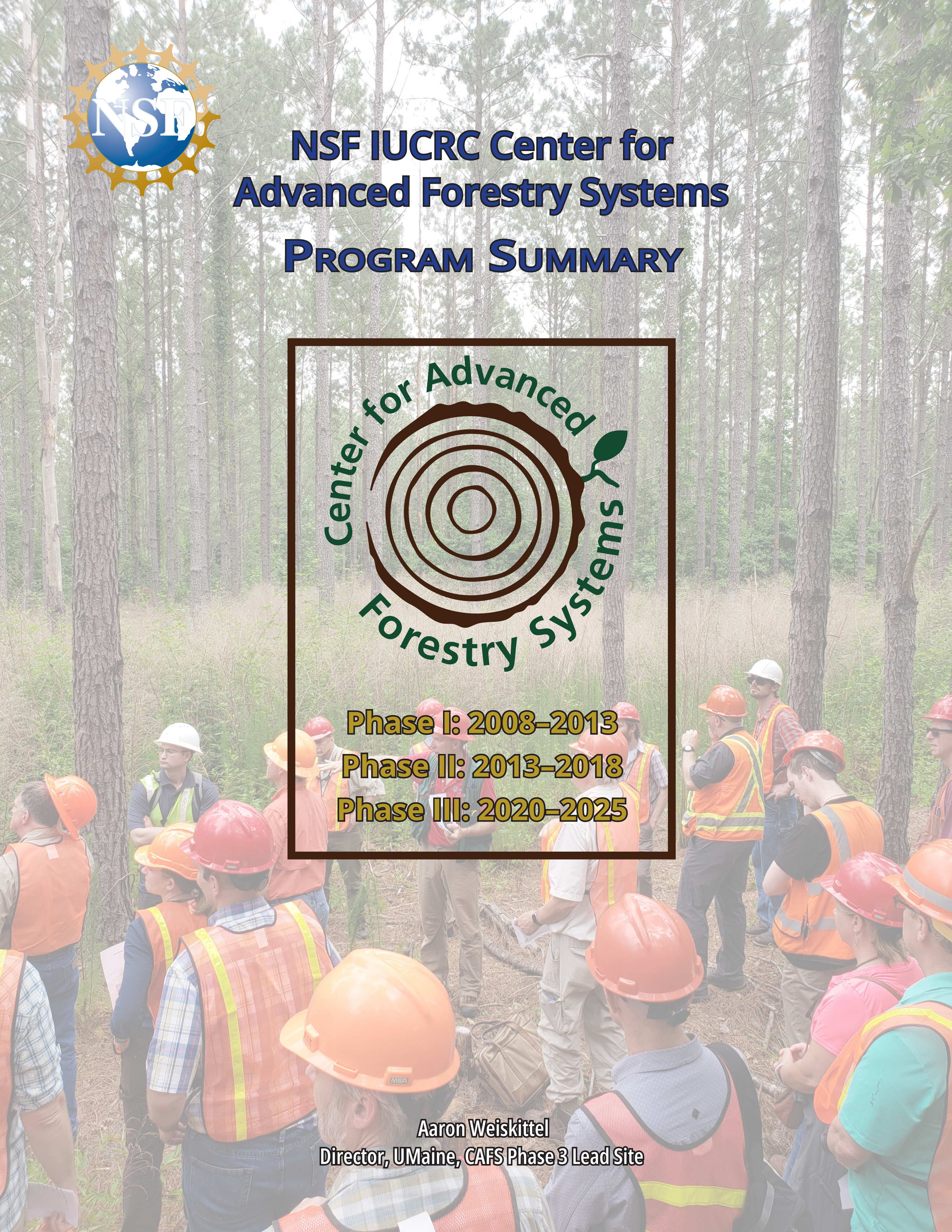


NSF IUCRC Center for Advanced Forestry Systems

Program Summary

Center for Advanced Forestry Systems

Phase I: 2008–2013
Phase II: 2013–2018
Phase III: 2020–2025

Aaron Weiskittel
Director, UMaine, CAFS Phase 3 Lead Site

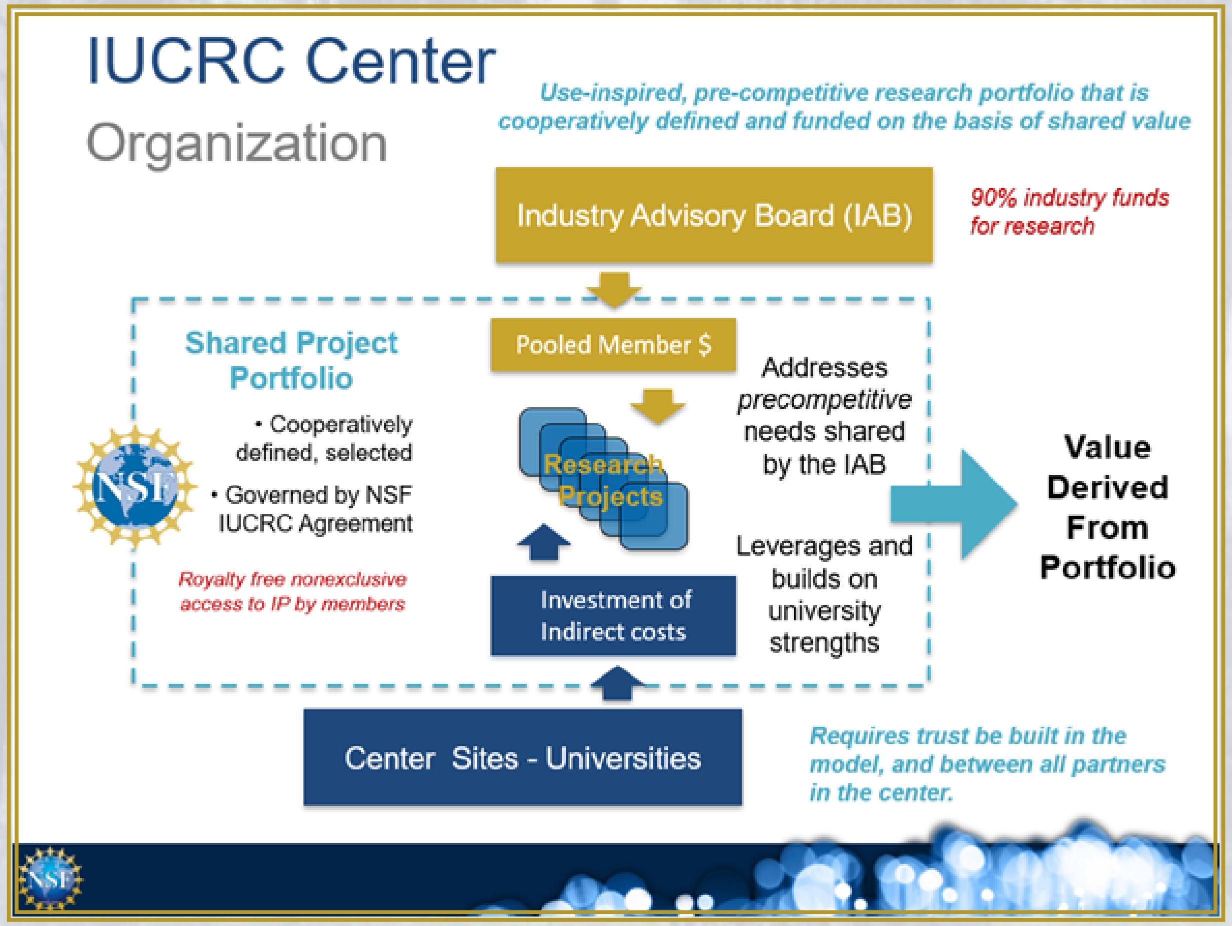
Vision

To actively support the US forest industry by solving problems with targeted, applied, and collaborative research coordinated across multiple universities.

Mission

Optimize genetic and cultural systems to produce high-quality raw forest materials for new and existing products by conducting collaborative research that transcends traditional species and disciplinary boundaries.

Please visit the CAFS webpage for access to annual reports, meeting webpages, and the latest updates.
crsf.umaine.edu/forest-research/cafs



EXECUTIVE SUMMARY

The Center for Advanced Forestry Systems (CAFS) was established in 2007 as an Industry-University Cooperative Research Center (IUCRC) through the National Science Foundation (NSF) to address the research needs of the forest sector, initially led by Dr. Barry Goldfarb of North Carolina State University with the involvement of several universities across the US and numerous Industry Advisory Board (IAB) members. Since 2018, CAFS has been led by Dr. Aaron Weiskittel and the University of Maine with successful graduation from the NSF IUCRC program expected at the end 2025. Since its inception, CAFS has supported collaborative research at multiple spatial and temporal scales, including molecular, cellular, individual-tree, stand, and ecosystem levels. This has resulted in:

- Increased forest productivity through improved silvicultural and genetic practices.
- Enhanced competitiveness of the US forest products sector.
- Development of improved decision-support tools for forest managers, such as growth and yield models and remote sensing technologies.
- Fostered the development and implementation of new technologies in forestry.
- Promoted sustainable forestry practices across the US.
- Training for numerous undergraduate and graduate students.

Specific research highlights include:

- Estimating a regional nitrogen fertilization response for Douglas-fir on late-rotation stands.
- Developing a consistent and biologically-meaningful metric of potential site productivity that can be related to a combination of environmental and edaphic factors and mapped across various regions.
- Synthesizing a nationwide forest measurements database, standardizing maximum carrying capacity modeling, and providing regionally relevant, national forest carrying capacity models.
- Examining drought-related physiological parameters and root morphological traits of various genotypes of western larch, black walnut, and coastal Douglas-fir.
- Minimizing both total and systematic error in satellite-derived maps for improved forest map accuracy.

These efforts have significantly impacted forest management practices and contributed to the sustainability and productivity of the nation's forests. This comprehensive report highlights the numerous outcomes, partnerships, and future potential of CAFS.

Note: Appendices noted in the following pages (IAB members, students, publications, and projects), as well as a downloadable pdf of this report, are available on the CAFS IUCRC Program Summary webpage: https://crsf.umaine.edu/forest-research/cafs/program-summary/

> The IUCRC program allowed us to bring forest industry research programs, which had primarily been single-issue and regional in focus, under a national umbrella. This promoted an enhanced interdisciplinary and national perspective. IAB support and guidance facilitated collaborative and interdisciplinary research to address member needs. CAFS also proved to be an important networking venue for both industry and university scientists. This was especially true for younger industry and university participants as they could interact with peers and more senior leaders and become aware of the cutting-edge research from around the country. With the strong foundation established in Phase III, there is great enthusiasm for CAFS' future as a graduated IUCRC.

Dr. Barry Goldfarb, CAFS Phase 1 & 2 Director,
North Carolina State University

NC STATE UNIVERSITY

DIRECTOR'S LETTER

Dear CAFS Supporters and Partners,

As we reflect on the collaborative research and innovation at the Center for Advanced Forest Systems (CAFS), it is with immense pride and gratitude that I share a summary of our collective accomplishments, express sincere appreciation for the unwavering support of our numerous collaborators, and underscore the critical need for sustained efforts aligned with the broader mission of national science convergence and synthesis. Over its history, CAFS has been a cornerstone of collaborative forestry research. CAFS was established in 2007 to address challenges facing the wood products industry, landowners, and managers of the nation's forestland. To achieve this goal, CAFS successfully provided the administrative and funding structure needed for national, interdisciplinary, scientific collaboration. Over its three phases, CAFS has made significant progress in areas of applied forest science research related to remote sensing, precision management prescriptions, and decision-support modeling, to name a few.

As highlighted in this summative report, CAFS has evolved over time and continues to do so, yet has remained aligned with its original vision of unifying regional efforts into a national, comprehensive, and cohesive effort. This has been particularly evident in the last 5+ years of Phase 3 as research has converged in specific areas like remote sensing, forest health, and small area estimation. I fully believe that the next generation of valuable research and new knowledge will flourish and become sustainable through initiatives planned for CAFS following its graduation from the National Science Foundation's Industry/University Collaborative Research Center (IUCRC) program. Key strategies outlined in this report will help propel CAFS forward by streamlining governance, enhancing the value proposition for members, and improving marketing and communication strategies. CAFS' robust research portfolio encompasses many projects, with many involving multiple university sites, which makes evident the highly collaborative nature of the membership and the importance of cross-regional efforts, both critical for the program's long-term sustainability. What lays ahead would not be possible without the dedication, expertise, support, and multiple accomplishments from numerous individuals and organizations over the past 15 years. I would like to express my sincere gratitude to:

- ***Our Original Founders:*** Barry Goldfarb (North Carolina State University), Tom Fox (Virgina Tech), Glenn Howe (Oregon State University), and Charles Michler (Purdue University)
- ***Our Former/Current Participating Universities:*** Auburn University, University of Georgia, University of Florida, University of Idaho, University of Maine, North Carolina State University, Oregon State University, Purdue University, University of Washington, and Virginia Tech.
- ***Our Former/Current IAB Chairs:*** Marshall Jacobson (retired, Plum Creek), Julio Rojas (Weyerhaeuser), John Paul McTague (retired, Rayonier), Greg Johnson (retired, Weyerhaeuser), Tom Trembath (retired, Forest Investment Associates), Dale Hogg (Green Diamond), and Nathaniel Naumann (PotlatchDeltic).
- ***Our Long-Term Funders:*** Industry Advisory Board members and National Science Foundation.

This commitment to advancing forest science has been instrumental in driving our success. As we look to the future, the need for collaborative research and science synthesis has never been greater. Forests play a vital role in addressing some of society's most pressing challenges, including climate change, water security, and biodiversity conservation. To ensure the sustainable management of these valuable resources, we must expand our understanding of forest dynamics and management across diverse regions and forest types. We need innovative management strategies that enhance forest resilience and productivity in the face of climate change and other stressors. There is a need to promote the adoption of best management practices that minimize environmental impacts and maximize the benefits of forests for society. We must foster greater collaboration among researchers, policymakers, and practitioners to translate scientific knowledge into effective action. ***By aligning our future efforts with the broader mission of national science synthesis, we can ensure that forest management decisions are informed by the best available science and contribute to a more sustainable and resilient future for all.*** Further research is needed to optimize forest management systems and produce high-quality forest resources through collaborative, multi-disciplinary research that transcends regional and organizational boundaries while fostering the next generation of forestry leaders and innovators. Together, we can continue to advance forest science and make a lasting impact on the health and productivity of our nation's forests.

Thank you for your continued support of CAFS.

Sincerely,

Aaron Weiskittel, CAFS Director

Forest industry/university research cooperatives were a revolutionary development as far back as the 1950s. Prior to the development of the Center for Advanced Forestry Systems (CAFS) in 2007, however, each of these cooperatives generally confined their activities to the states where the universities were located. The advent of CAFS through the National Science Foundation dramatically improved this situation by incentivizing forest researchers and forest companies to collaborate nationally on scientific questions. For the first time, forest researchers shared ideas, data sets, and field experiments across forest types in the US. A good example of this collaboration was work by Bose et al. (2018) to better understand the relative effects of commercial thinning treatments in Southeast, Northeast, and Pacific Northwest forests.

Dr. Robert Wagner, UMaine Site Director, Phase 1 & 2

1865 THE UNIVERSITY OF MAINE

Founding & History

The Center for Advanced Forestry Systems (CAFS) was founded in 2007 to address forest management and decision-support research needs of the nation's forest products sector (Figure 1). It was established as an Industry-University Cooperative Research Center (IUCRC) through the National Science Foundation (NSF). The four founding university sites were North Carolina State University (NCSU), Oregon State University (OSU), Purdue University (PU), and Virginia Tech (VT). Since then, CAFS has expanded to ten university sites, including Auburn University (AU), the University of Florida (UF), University of Georgia (UGA), University of Idaho (UI), University of Maine (UM), and the University of Washington (UW). Phase II for CAFS was approved for all sites effective October 1, 2013. CAFS received Phase III NSF funding for all sites, except VT, UF, and AU, from December 15, 2019 to November 30, 2024.

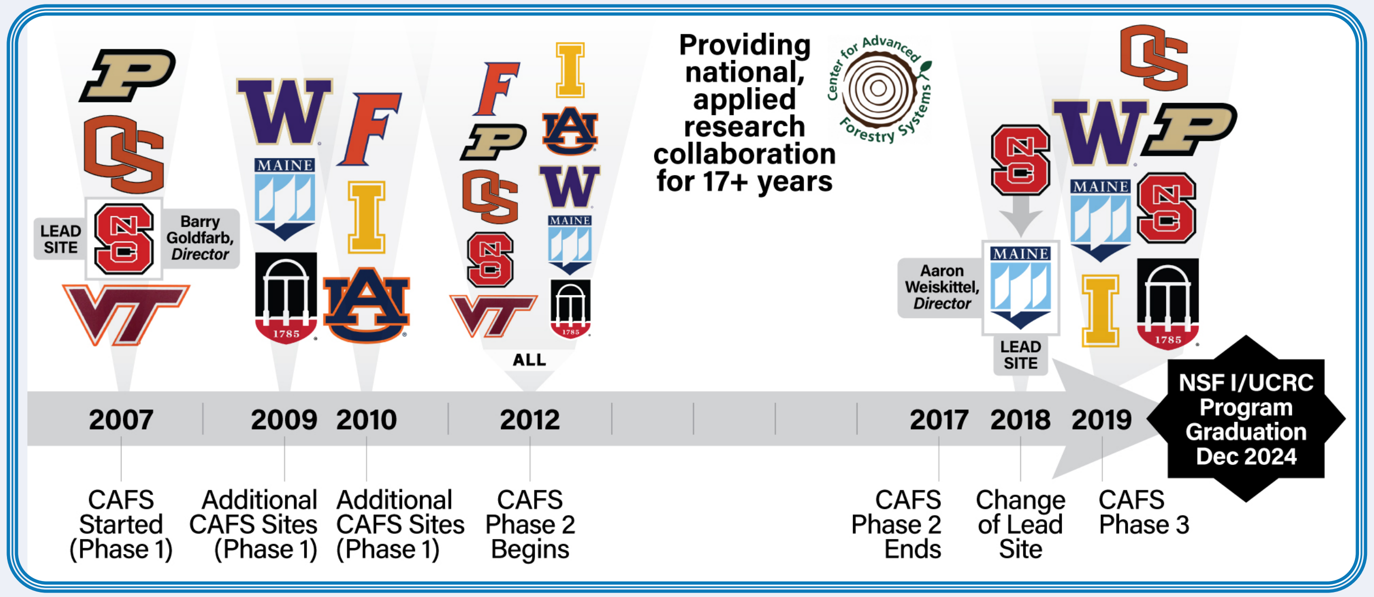


***Figure 1.** CAFS Site Participation Timeline.*

CAFS is set to become one of the first graduated NSF IUCRC centers in 2025 and has been the largest in the NSF IUCRC portfolio. A primary objective of CAFS was to unify regional cooperatives under a consistent structure and function to leverage existing resources and create national synergies, particularly in the era of emerging technologies like AI and advanced remote sensing (Figure 2). This combination of expertise and assets was critical to leveraging capacity given the increasing nature of innovations across the sector despite declining US Federal R&D expenditures (Figure 3).

Based on NSF expectations, CAFS was administered by NCSU's Dr. Barry Goldfarb as the IUCRC Center Director from 2007 to 2017 with support from Site Directors, a structure that has continued to evolve across the three 5-year phases (Table 1). Dr. Goldfarb led CAFS through Phase I and much of Phase II, retiring from NCSU in 2019. Dr. Aaron Weiskittel has led CAFS since 2017, and successfully secured Phase III funding in 2019. Similar to the change in Center Directors, the University Site Directors and Industrial

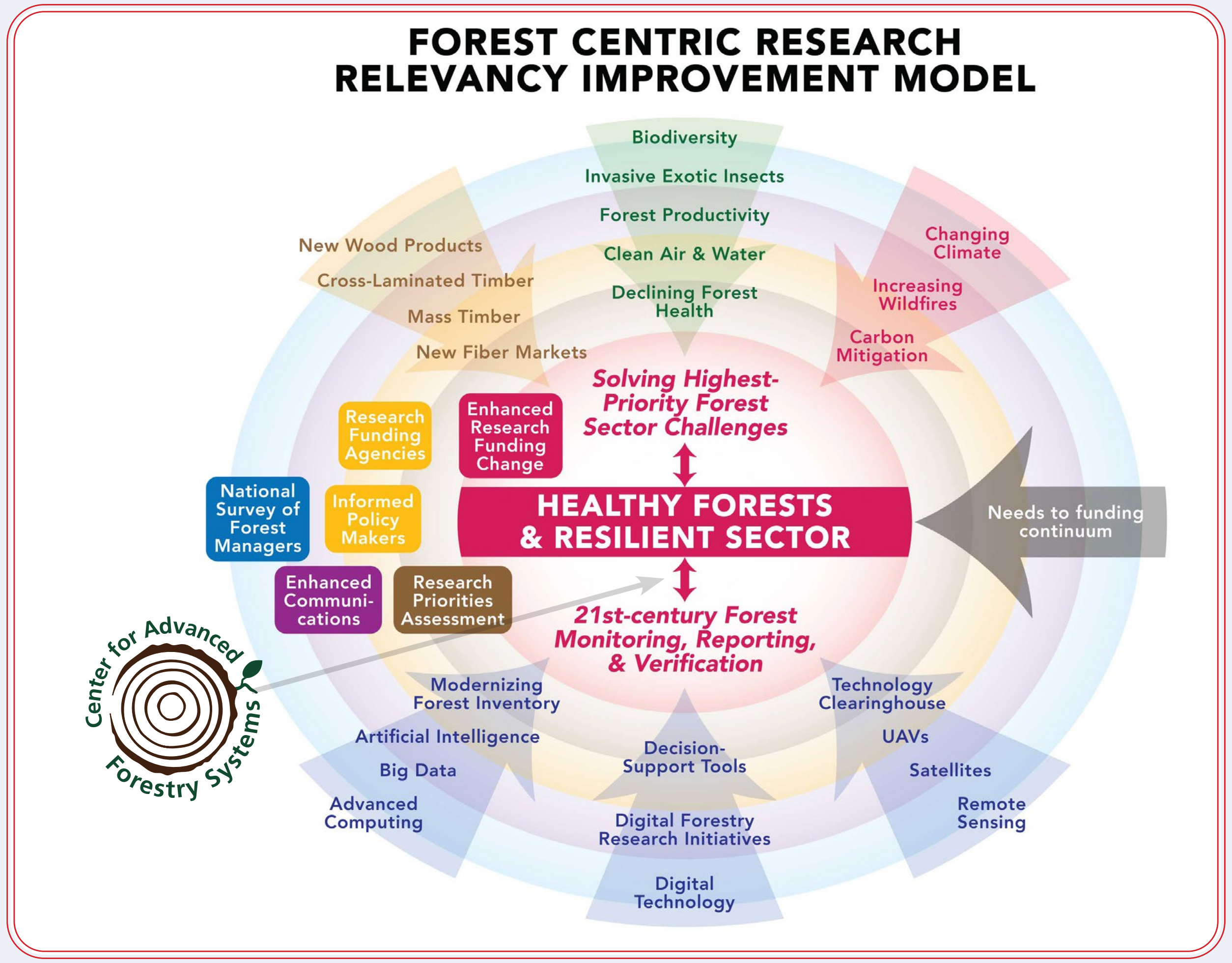


Figure 2. *CAFS Structure Unifying Regional Cooperatives and Leveraging Resources.*

Table 1. CAFS Center and University Site Directors Across the Three 5-year Phases of NSF Funding.

Site	Years Active	Phase I	Phase II	Phase III
CAFS Center Director	2007–	Barry Goldfarb	Barry Goldfarb	Aaron Weiskittel
Oregon State University	2007–	Glenn Howe	Glenn Howe	Carlos Gonzalez-Benecke
North Carolina State University	2007–	Barry Goldfarb	Barry Goldfarb	Rachel Cook
Virgina Tech	2007–2017	Thomas Fox	Thomas Fox/ Harold Burkhard	—
Purdue University	2007–	Charles Michler	Charles Michler	Doug Jacobs
University of Washington	2009–	David Briggs	Gregorry Ettl	Eric Turnblom
University of Georgia	2009–	Michael Kane	Cristian Montes	Joseph Dahlen/ Bronson Bullock
University of Maine	2009–	Robert Wagner	Robert Wagner	Aaron Weiskittel
University of Idaho	2010–	Mark Coleman	Mark Coleman	Andrew Nelson
University of Florida	2010–2015	Eric Jokela	—	—
Auburn University	2010–2015	Scott Enebak	—	—

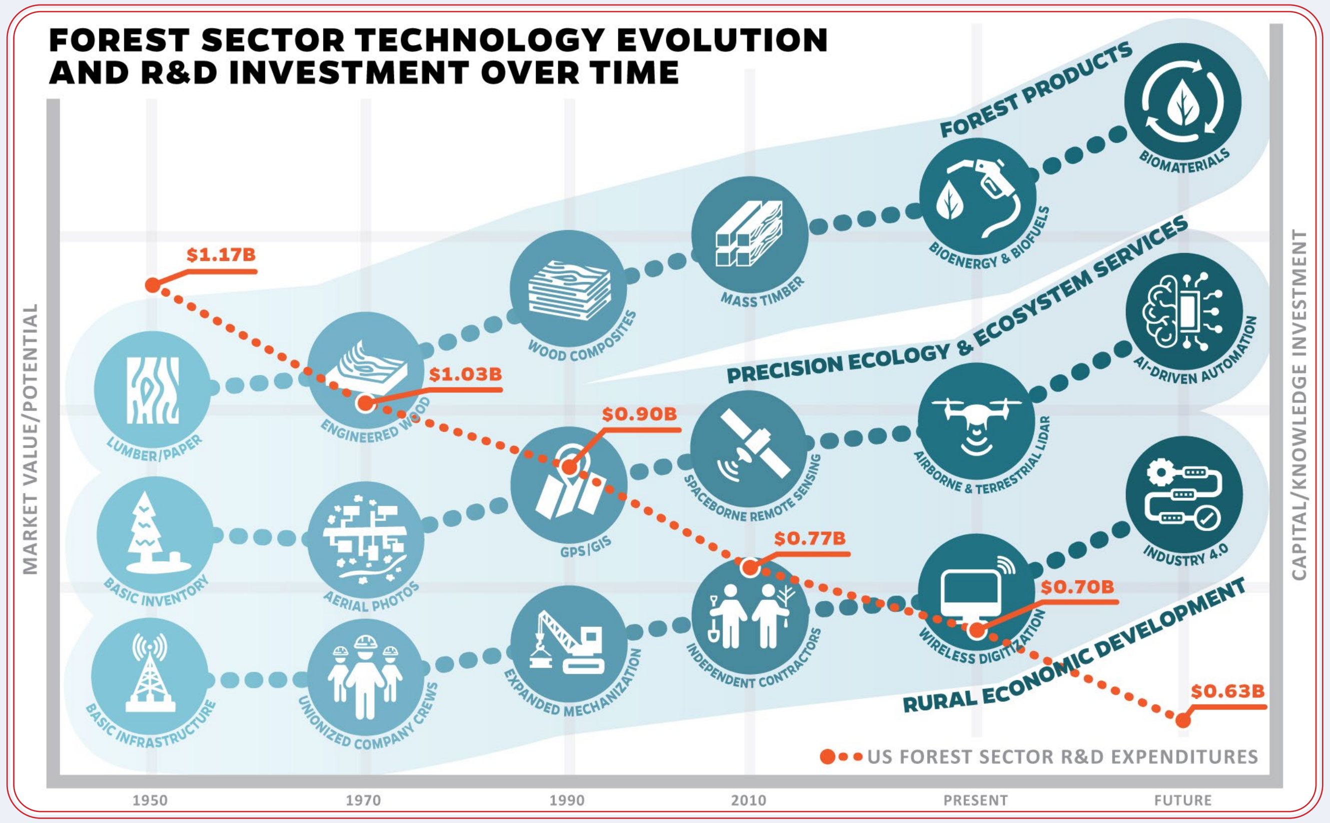


Figure 3. *Forest Sector Technology Evolution and R&D Investment.*

Advisory Board (IAB) Executive Board members have evolved over the years (Table 2). IAB Executive Board Chairs have included Marshall Jacobson (Plum Creek) in Phase I, Julio Rojas and Greg Johnson (Weyerhaeuser) and John Paul McTague (Rayonier, Inc.) in Phase II, and Dale Hogg (Green Diamond), Tom Trembath (retired, Forest Investment Associates), and Nathaniel Naumann (PotlatchDeltic) in Phase III.

Table 2. CAFS Industry Advisory Board (IAB) Executive Members by University and Phase.

Site	Phase I	Phase II	Phase III
Oregon State University	Dave Rumker (Campbell Group)	Sara Lipow (Roseburg Forest Products)	Dale Hogg* (Green Diamond)
North Carolina State University	Jim Gent (Rayonier, Inc.)	John Paul McTague* (Rayonier, Inc.)	Corey Dukes (Timberland Investment Resources, LLC)
Virgina Tech	Julio Rojas (Weyerhaeuser)	Julio Rojas*/ Greg Johnson* (Weyerhaeuser)	—
Purdue Univers-ty	Guillermo Pardillo (ArborAmerica)	Guillermo Pardillo (ArborAmerica)	Guillermo Pardillo (Arbor America)
University of Washington	Randall Greggs (Green Diamond)	Dave Lortz (Campbell Global)	Pat Clune (Roseburg Forest Products)
University of Georgia	Marshall Jacobson* (Plum Creek)	John Pait (ArborGen, LLC)	Nate Naumann (Potlatch-Deltic)
University of Maine	John Bryant (BBC Land, Inc.)	John Bryant (BBC Land, Inc.)	Ian Prior (Seven Is-lands Land Compa-ny)
University of Idaho	Bruce Ripley (Forest Capital)	Bruce Ripley (Hancock Forest Management)	Zach Grover (Manulife)

**CAFS IAB Executive Chair*

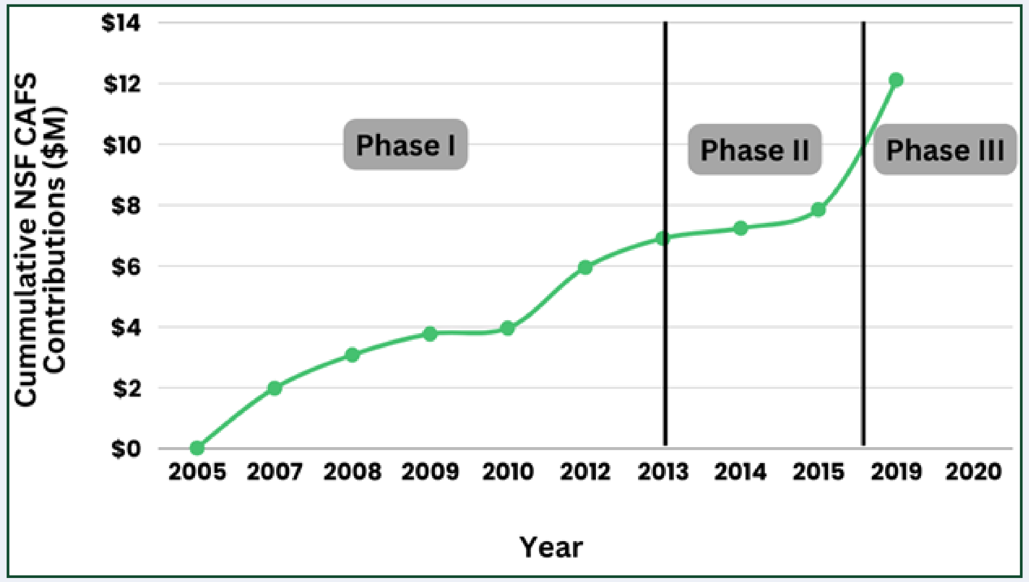


Figure 4. *Cumulative NSF Contributions Over Three CAFS Phases.*

CAFS funding has been driven by strong membership and numerous NSF awards (Table 3, Figure 4). Despite changes and consolidation in the forest sector, active membership has remained steady and currently includes over 100 members (Figure 5, Appendix 1). NSF contributions across the CAFS Sites has varied due to supplemental funding opportunities and prior direct financial support for the lead site, but has exceeded $1M for all institutions, except Auburn and the University of Florida (Figure 6). Supplemental funding opportunities have included Collaborative Research, Research Experience for Undergraduates (REU), Skills Training in Advanced Research & Technology (START), and Non-Academic Research Internships for Graduate Students (INTERN) awards, which were received across three CAFS phases and leveraged synergistic opportunities by the ongoing research projects described below.

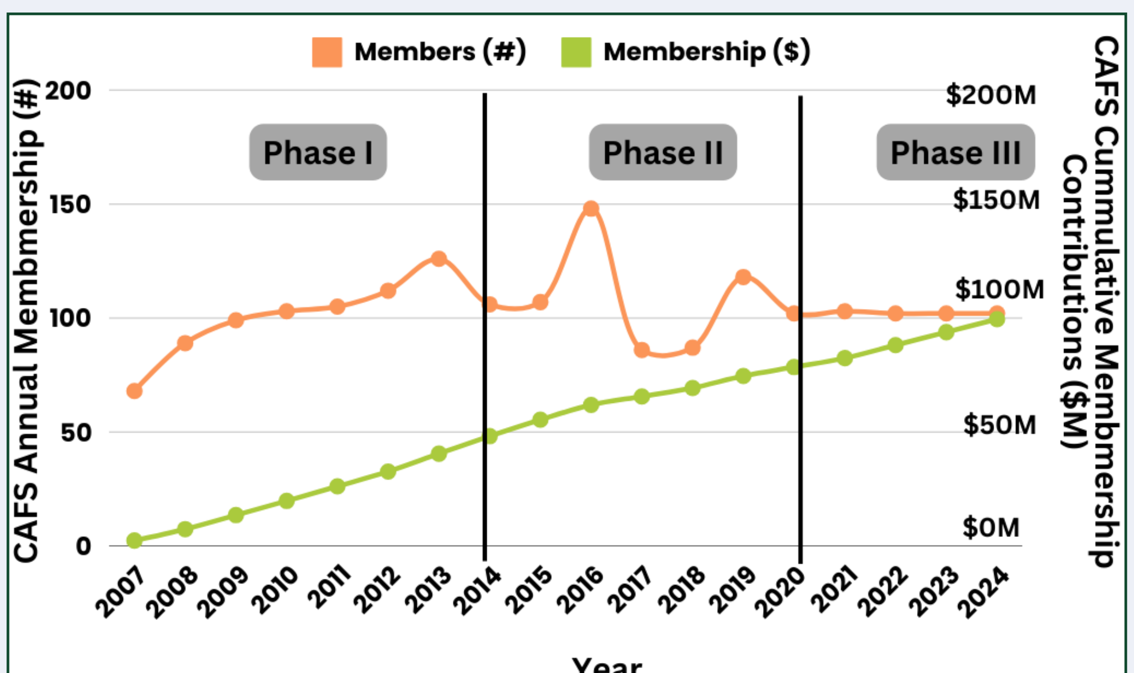


Figure 5. *CAFS Membership Across All Three Phases.*

Table 3. NSF Awards to CAFS Researchers

Phase	Year	NSF Award #	Site Directors	Organization	Funding Award
I	2005	0555887	Thomas Fox	Virginia Tech	$10,000
I	2005	0556131	Barry Goldfarb	North Carolina State University	$10,000
I	2007	0736340	Thomas Fox	Virginia Tech	$357,200
I	2007	0736283	Glenn Howe	Oregon State University	$318,000
I	2007	0736399	Charles Michler	Purdue University	$374,000
I	2007	0736402	Barry Goldfarb	North Carolina State University	$915,834
I	2008	0855776	Michael Kane	University of Georgia	$357,995
I	2008	0855370	Robert Wagner	University of Maine	$357,350
I	2008	0855690	David Briggs	University of Washington	$381,598
I	2009	0968821	Mark Coleman	University of Idaho	$410,000
I	2009	0934138	Eric Jokela	University of Florida	$275,000
I	2010	1031473	Thomas Fox	Virginia Tech	$195,078
II	2013	1360860	Scott Enebak	Auburn University	$300,000
II	2012	1238324	Barry Goldfarb	North Carolina State University	$1,175,190
II	2012	1238319	Charles Michler	Purdue University	$208,000
II	2012	1238265	Thomas Fox	Virginia Tech	$300,000
II	2012	1238305	Glenn Howe	Oregon State University	$299,998
II	2013	1361543	Robert Wagner	University of Maine	$367,999
II	2013	1361755	Cristian Montes	University of Georgia	$300,000
II	2014	1439653	Gregory Ettl	University of Washington	$325,000
II	2015	1535587	Harold Burkhart	Virginia Tech	$66,526
II	2015	1539982	Aaron Weiskittel	University of Maine	$66,526
II	2015	1534751	Eric Turnblom	University of Washington	$66,526
II	2015	1540045	Mark Coleman	University of Idaho	$411,964
III	2019	1916720	Cristian Montes	University of Georgia	$600,000
III	2019	1915078	Aaron Weiskittel	University of Maine	$793,118
III	2019	1916552	Rachel Cook	North Carolina State University	$601,311
III	2019	1916793	Carlos Gonzalez Benecke	Oregon State University	$555,000
III	2019	1916587	Douglass Jacobs	Purdue University	$458,708
III	2019	1916155	Eric Turnblom	University of Washington	$500,000
III	2019	1916699	Andrew Nelson	University of Idaho	$748,578

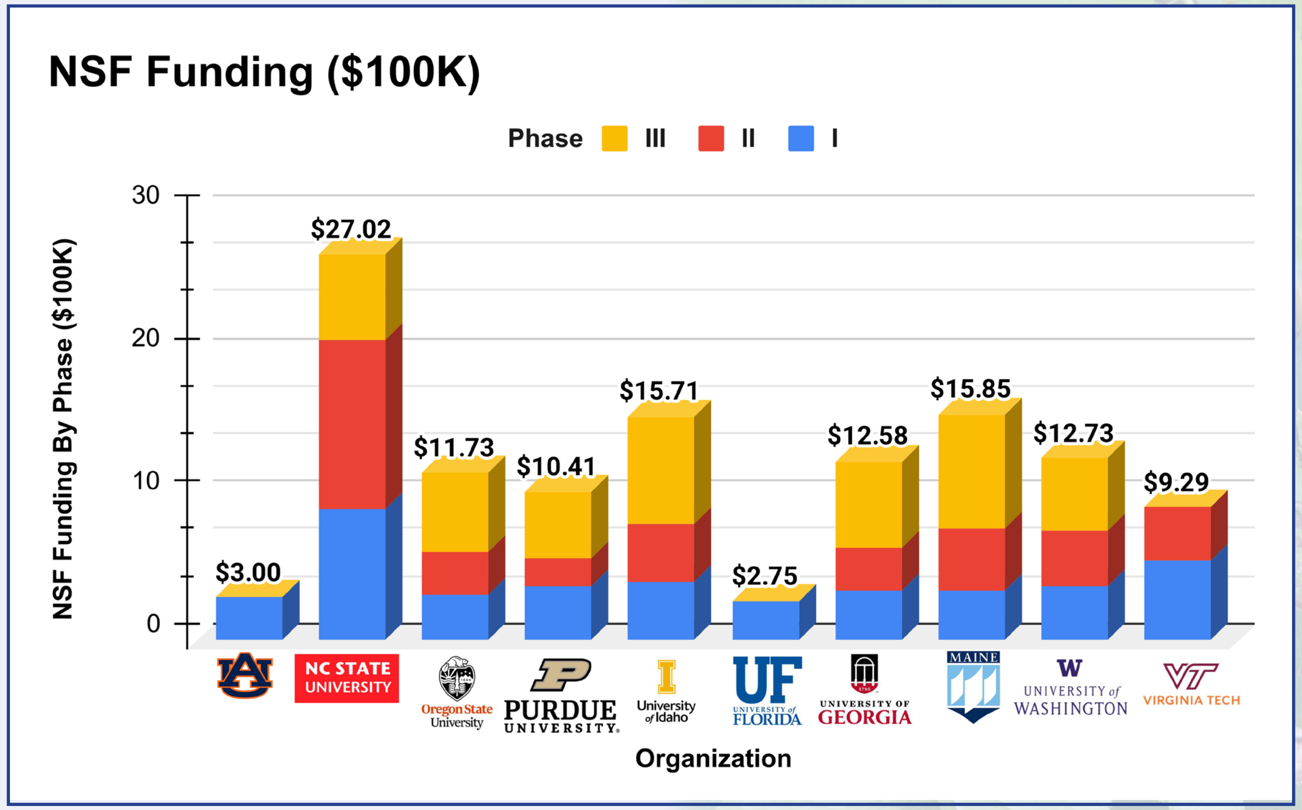


Figure 6. NSF Cummulative Supplemental Funding Across CAFS Sites.

CAFS research has supported both undergraduate and graduate students over the years (Figure 7, Appendix 2), and has involved numerous post-doctoral researchers (Table 4). This research has resulted in numerous outcomes, including peer-reviewed publications, technical reports, and conference presentations across all three CAFS phases (Table 5, Figure 8). **CAFS students have been hired by IAB members, pursued additional educational careers, and become faculty members. Peer-reviewed journal articles have appeared in numerous top scientific outlets** (Appendix 3); *Forest Ecology and Management* (Impact Factor = 3.7) was a common outlet for CAFS publications with studies ranging from modeling mid-rotation fertilizer responses to the impact of forest management on carbon balance and the influence of silvicultural treatments on biomass accumulation. Several articles appeared in the *Canadian Journal of Forest Research* (Impact Factor = 2.2), covering topics such as cellulose microfibril angle in *Pinus taeda*, genetic variation in wood stiffness of coastal Douglas-fir, the effects of fertilizer applications on *Pinus taeda* growth, and genome size variation in the pine fusiform rust pathogen. Other journal outlets included *Ecology* (Impact Factor = 4.7), *Tree Physiology* (Impact Factor = 3.5), *Forest Science* (Impact Factor = 1.5), and *Remote Sensing of Environment* (Impact Factor = 11.1). Most of the journal articles had involvement from CAFS students and post-doctoral researchers, highlighting the key role of CAFS for training and mentoring.

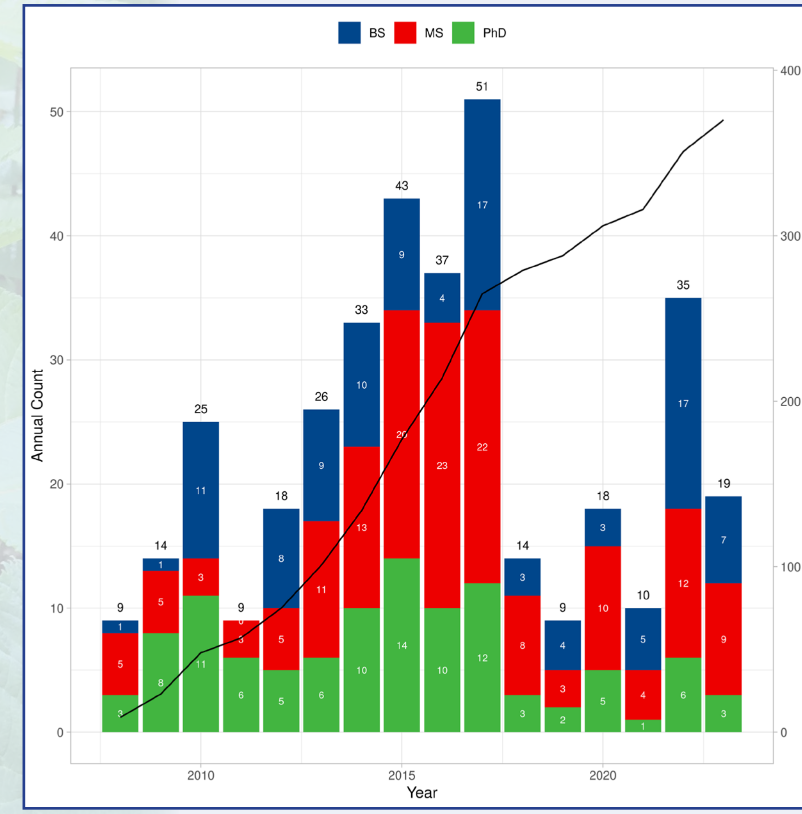


Figure 7. CAFS Student Engagement by Year and Student Type.

Table 4. Primary Expertise by CAFS Sites.

Site	Forest Type	Genetics	Biotech	Soils	Eco-Physiology	Growth & Yield	Wood Quality	Remote Sensing
NC State University	Southern Pine; Eucalyptus	✓	✓	✓	✓	✓		✓
Oregon State University	Douglas-fir; Eucalyptus	✓	✓		✓	✓	✓	
Purdue University	Upland Hardwoods	✓	✓	✓	✓	✓		✓
Virginia Tech	Southern Pine Hardwoods	✓	✓		✓	✓	✓	
University of Georgia	Southern Pine				✓	✓	✓	
University of Florida	Southern Pine	✓	✓	✓	✓			
The University of Maine	Mixed Forest			✓	✓	✓	✓	✓
University of Washington	Douglas-Fir			✓		✓	✓	✓
University of Idaho	Mixed Conifer	✓	✓	✓	✓			✓

Table 5. CAFS Post-doctoral Researchers and Associated Project, Mentor(s), and University.

Phase	Project #	Post-Doc	Project Title	Mentor(s)	University
I	12.39	Melissa Pisaroglo de Carvalho	Modelling Tree-to-Tree Competition in Forest Trials to Understand its Mechanisms	Gezan	FL
I	9.16	Finto Antony	Integrating Wood Quality Predictions into Growth and Yield Models for Evaluating Advanced Genotypes and Silvicultural Responses	Daniels	GA
I	13.34	Mohammad Bataineh	Individual Tree Response to Commercial Thinning in Maine: Influence of Competition, Site, and Treatment Regime	Wagner	ME
I	10.32	Mathew Olson	Examining the Influence of Precommercial and Commercial Thinning in Balsam fir and Red Spruce Stands across Maine	Wagner	ME
I	9.10	Rongxia Li	Refinement of Regional Growth and Yield Models for Naturally-Regenerated, Mixed Species Stands in the Northeast	Weiskittel	ME
I	9.10	Erin Simons	Refinement of Regional Growth and Yield Models for Naturally-Regenerated, Mixed Species Stands in the Northeast	Weiskittel	ME
I	10.33	Jose Zerpa	Use of Stable Isotopes to Trace the Fate of Applied Nitrogen in Forest Plantations to Evaluate Fertilizer Efficiency and Ecosystem Impacts	Fox	VT
I	10.33	Chris Kiser	Use of Stable Isotopes to Trace the Fate of Applied Nitrogen in Forest Plantations to Evaluate Fertilizer Efficiency and Ecosystem Impacts	Fox	VT
I	FPC	Christine Blinn	Application of Remote Sensing to Loblolly Pine Management in the South	Fox	VT
I	9.22	Nick Vaughn	Remote Sensing for Measuring and Monitoring the Response of Plantations to Intensive Management	Moskal	WA
I	9.22	Guang Zheng	Remote Sensing for Measuring and Monitoring the Response of Plantations to Intensive Management	Moskal	WA
I	9.19	Kim Littke Hanft	Understanding Site-Specific Factors Affecting the Nutrient Demands and Response to Fertilizer by Douglas-fir	Harrison	WA
I	10.24	Rapeepan Kantavichai	Biomass Growth and Yield of Intensively Managed Coastal Douglas-fir Plantations	Briggs	WA
II	17.70	Arun Bose	The Rise of Commercially Less Desirable Species in Maine: Identification, Characterization, and Associated Driving Factors	Wagner/ Weiskittel	ME
II	18.71	Josh Puhlick	Development of Small Tree Growth and Survival Equations for the Commercially Important Species in the Acadian Region	Weiskittel	ME
II	18.72	Cen Chen	Modeling the Influence of Spruce Budworm on Forest Productivity	Weiskittel	ME
II	16.65	Christian Kuehne	Understanding and Modeling Competition Effects on Tree Growth and Stand Development across Varying Forest Types and Management Intensities	Weiskittel	ME
II	14.49	Matthew Sumnall	Use of Airborne Laser Scanning to Determine Crown Dimensions of Individual Trees in Study	Fox	VT
II	16.67	Mary Ridout	Improving White Pine Seedling Survival by Combining Blister Rust Resistance with Defense-enhancing Endophytes	Newcombe	ID
III	19.76	Jaslam Poolakkal	Assessing and Mapping Regional Variation in Site Carrying Capacity	Kimsey	ID
III	20.78	Andrei Toca	Intraspecific Hydraulic Responses of Commercial Tree Seedlings to Nursery Drought Conditioning	Jacobs/ Nelson	PU/ID
III	20.79	Kasey Legaard	Multi-Regional Evaluation of New Machine Learning Algorithms for Mapping Tree Species Distribution and Abundance	Weiskittel	ME
III	21.87	Andrew Trlica	Linking Leaf Area Index and Remote Sensing Across Different Forest Types	Cook	NC
III	24.107	Sukhyun Joo	Using Small Area Estimation and 3D-NAIP/Sentinel-derived Variables for Multivariate Prediction of Stand Attributes	Temesgen	OR

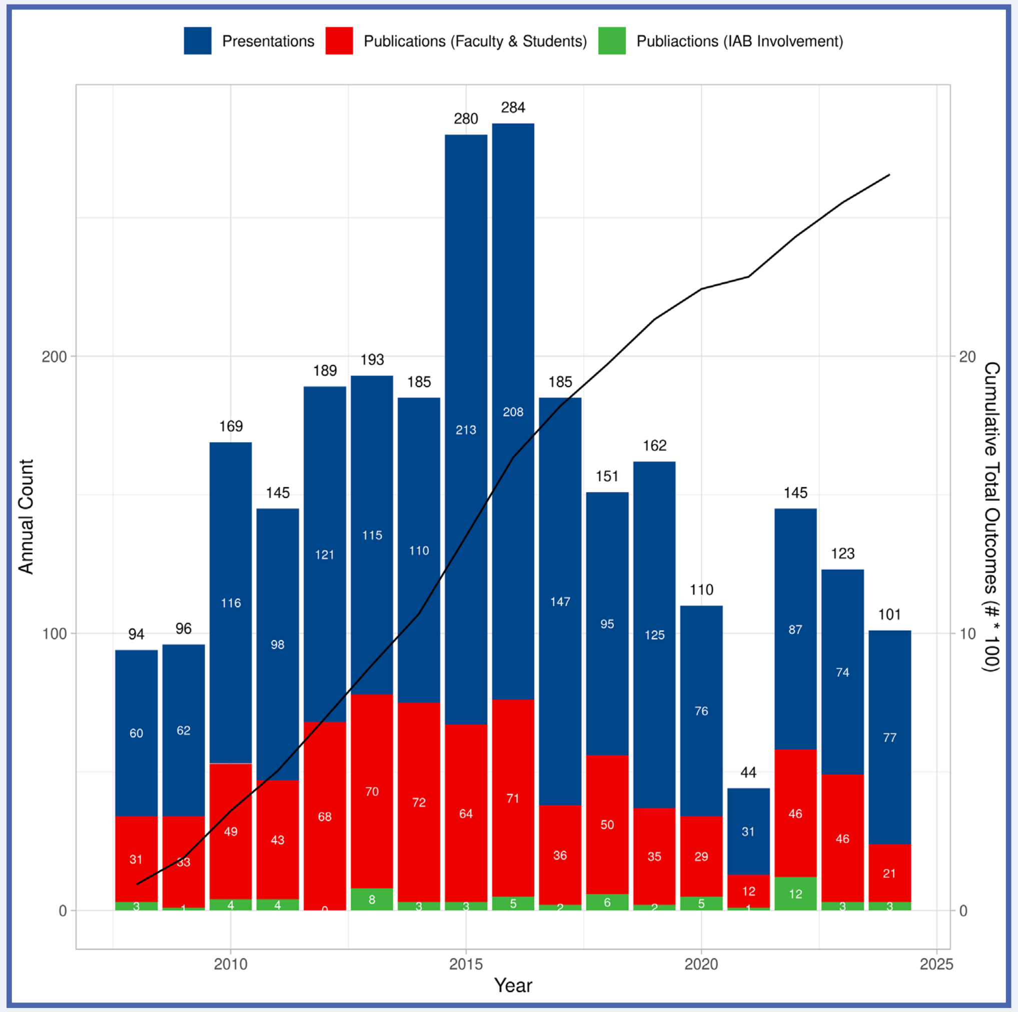


Figure 8. *Annual and cumulative outcomes from CAFS research including presentations, publications involving CAFS faculty and students, and publications involving CAFS IAB members.*

> The Center for Advanced Forestry Systems (CAFS) has a strong history of fostering collaboration between academia, industry, and government to advance forest science. As a former Industry Advisory Board member, I witnessed firsthand how CAFS created a dynamic environment where bright minds came together to tackle critical challenges in forestry. The center has made significant contributions in areas like forest genetics, decision-support tools, and remote sensing, helping to bridge the gap between research and practical applications. However, as the forestry industry evolves in an increasingly competitive world, CAFS must sharpen its focus on delivering solutions that directly address industry needs. Stronger alignment with operational challenges and emerging technologies will ensure its continued impact. With the right strategy, CAFS has the potential to remain a driving force in forestry innovation for years to come.

Julio Rojas, CAFS Phase 2 IAB Executive Committee Chair,
Weyerhaeuser

Research & Activities

CAFS was centered around the top forest science academic institutions across the US and the unique expertise that each brought to the collective effort (Table 6, Figure 9). CAFS research leveraged these collaborative synergies and was need- and member-driven as the Industrial Advisory Board (IAB) was instrumental in identifying key research priorities. Over time, CAFS pursued a diverse portfolio of projects in the areas of genetics, forest health, growth and yield modeling, wood quality, forest management, and remote sensing. Across the three phases, a total of nearly 100 projects have been initiated, with 37% of them being multi-site efforts (Figure 10; Appendix 4). These projects have been mostly balanced across the various focal areas, with a slightly higher emphasis on forest management, genetics, and growth and yield modeling (Figure 11). In Phase III, a greater and growing emphasis was on multi-site efforts, particularly remote sensing projects.

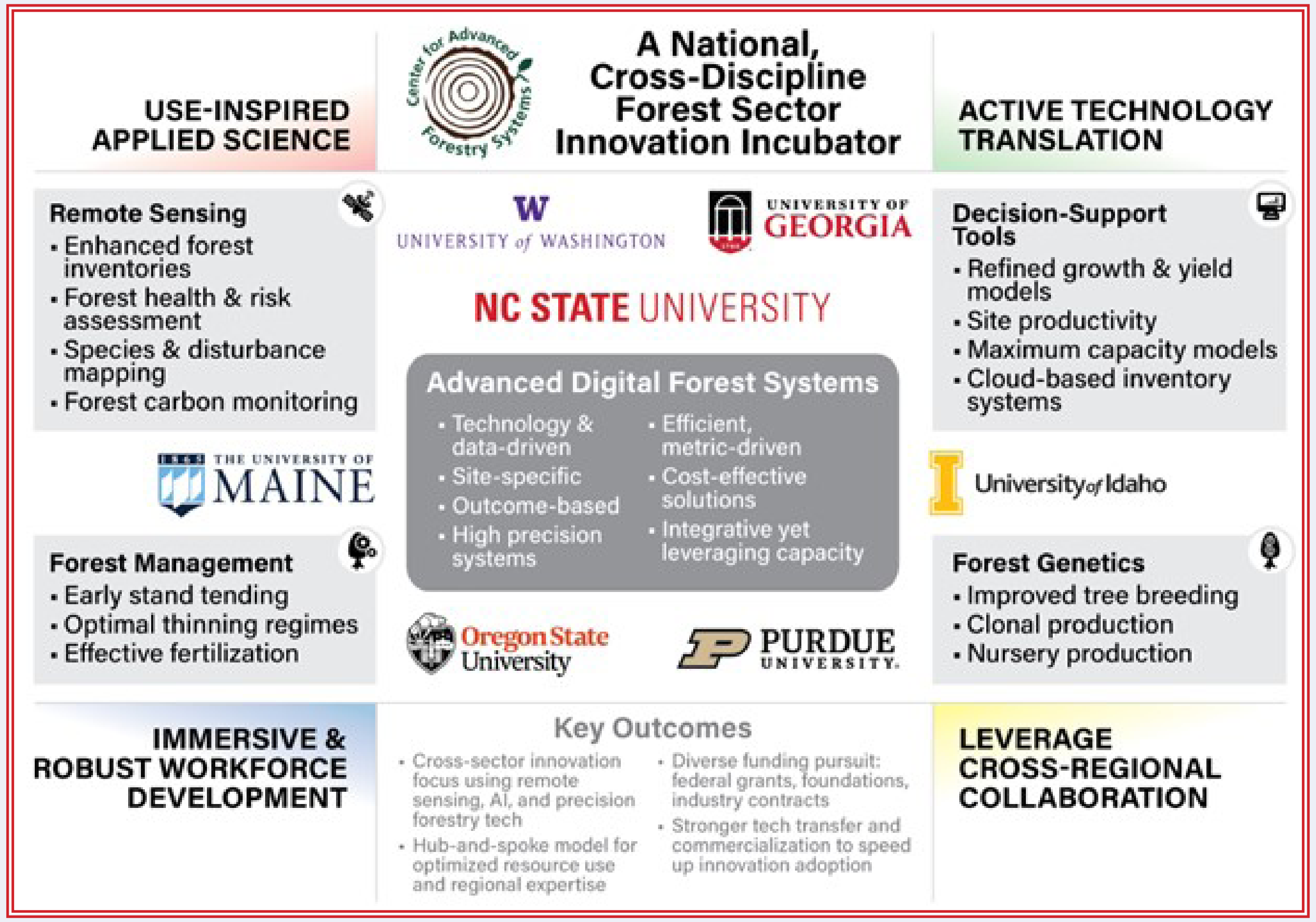


Figure 9. *Synergistic linkage of institutional capacity and expertise across the individual CAFS Sites.*

Table 6. Summary of Key Accomplishments and Outcomes Across the Three 5-year phases of CAFS.

Metric	Phase I	Phase II	Phase III	Total
University Sites				
Number of Active Sites	9	10	7	-
Research Activity				
Number of Center Projects	41	25	32	98
Multi-Site Projects	7	9	23	39
Intellectual Property				
Inventions Disclosed	0	1	0	1
Licensing Agreements	0	0	0	0
Patent Applications	1	0	0	1
Patents Granted	1	0	0	1
Inventions Producing Royalties	11	4	0	15
Dollar Value of Royalties Produced	0	0	0	0
Software Copyrights	0	0	0	0
Publications				
Number of Presentations Made	518	646	345	1,509
Faculty & Student Publications Based on Center Research	194	271	154	619
Publications Co-authored with Industry Members	12	21	24	57
Total by Phase:	724	938	523	2,185
IUCRC Graduate Degrees Awarded				
Bachelors	20	36	25	81
Masters	19	77	41	137
Doctorates	41	46	20	107
Total by Phase:	80	159	86	325
IUCRC Alumni Career Outcomes				
IUCRC Graduates Hired by I/URC Members (nonspecific)	15	7	37	59
info below not collected until 2014				
IUCRC Graduates Hired by Indus-try Members	6	17	0	23
IUCRC Graduates Hired by Government Members	7	5	3	15
IUCRC Graduates Hired by Non-Member Industry Firms	1	8	2	11
IUCRC Graduates Hired by Non-Member Government Agencies	1	3	0	4
IUCRC Graduates Taking Faculty Positions	0	4	8	12
IUCRC Graduates Taking Postdoc Positions	1	10	0	11
IUCRC Graduates Continuing Education/Advanced Degree	1	8	10	19
IUCRC Graduates Career Outcome Unknown/Not Reported	1	15	26	42

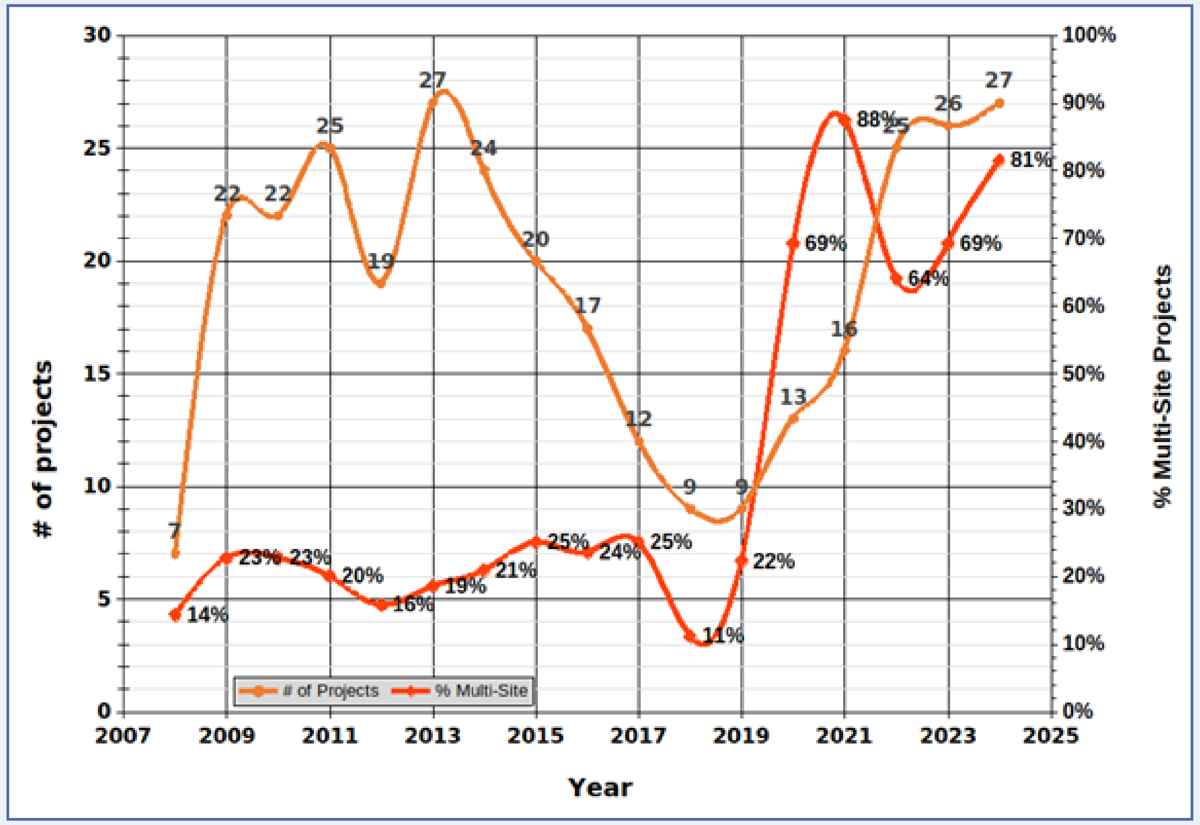


Figure 10. *CAFS IAB approved research projects over time with % being multi-site collaborative efforts.*

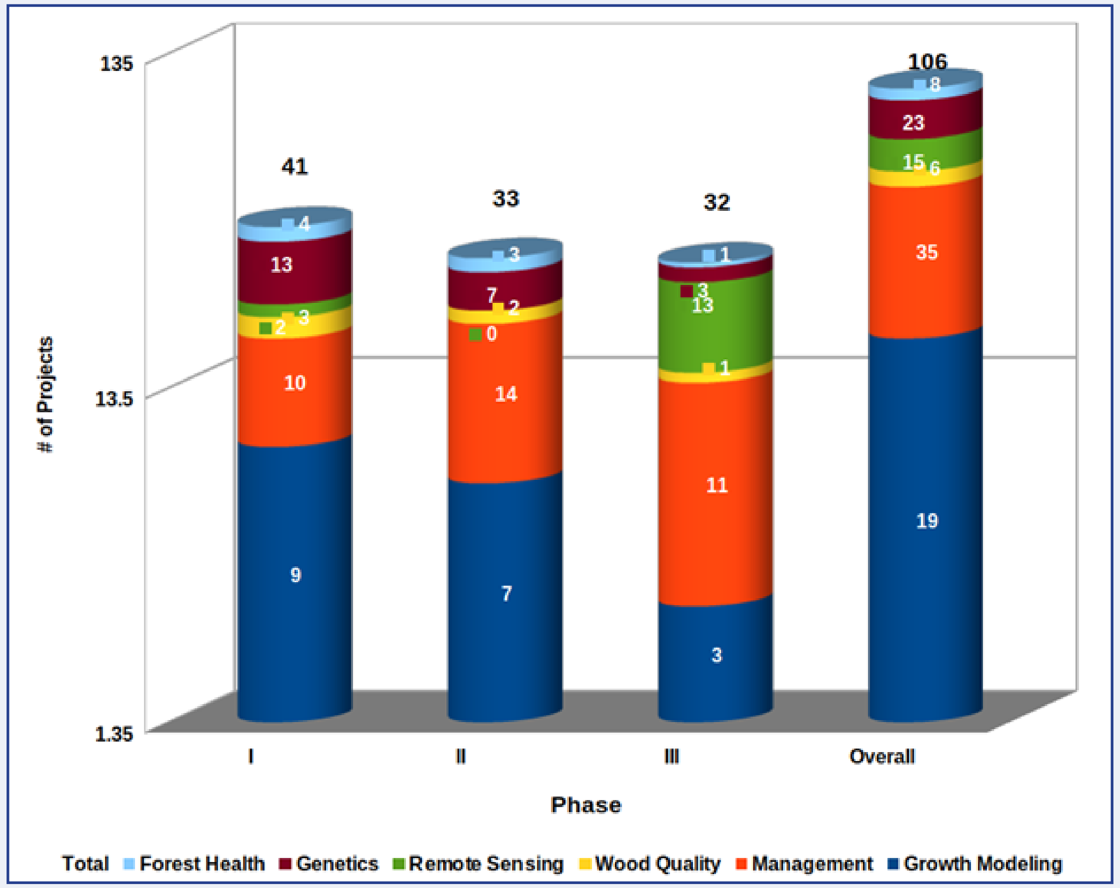


Figure 11. *CAFS IAB Approved Research Projects by Focal Area and Phase. Broad spectrum showcases the balanced portfolio over time with an increasing emphasis on remote sensing applications.*

Highlights

1. **Increased Forest Productivity:** CAFS research has led to increased forest productivity through the development of improved silvicultural and genetic practices. Examples include: (1) how fertilization, site preparation, and competition control significantly influence the productivity of loblolly and slash pine plantations; (2) role of genetics in determining wood properties and biomass production; and (3) variation in leaf area index and light interception are important factors influencing forest growth and productivity.
2. **Enhanced Competitiveness:** CAFS research has enhanced the competitiveness of the US forest products industry by providing solutions to sector challenges. This has included research addressing environmental variability, role of product markets, value of ecosystem services provided by managed forests, and strategizes for optimizing carbon or wildlife habitat.
3. **Improved Decision-Support Tools:** CAFS research has led to the development of improved decision-support tools for forest managers, such as growth and yield models, geospatial products, and scenario analysis frameworks. This has influenced the widely used Forest Vegetation Simulator, refined nationally-consistent estimates of maximum stand density index, and digital soil maps aligned with key forest attributes.
4. **New Technologies:** CAFS research has fostered the development and implementation of new technologies in forestry, such as unmanned aerial vehicles (UAVs), Light Detection and Ranging (LiDAR), and satellites like Landsat or Sentinel. For example, the LiDAR applications ranged from capturing tree crown formation and estimating leaf area index (LAI) to predicting aboveground biomass in mixed-species forests. Satellite data helped to quantify forest structure and composition, particularly providing estimates of deciduous competition in pine stands. These technologies lead to more informed near-time decision-making in forestry.
5. **Sustainable Forestry:** CAFS research has promoted sustainable forestry practices by providing a better understanding of the interactions between forest ecosystems and human activities. This includes examining the long-term compositional dynamics of mixedwood stands under different silvicultural regimes and the influence of partial harvesting and site factors on natural regeneration. CAFS research also focused on the impacts of forest management on ecosystem carbon storage and biodiversity values across managed landscapes. CAFS research also improved the understanding of soil nutrients and characteristics, while also studying the long-term effects of nitrogen fertilization on forest productivity.
6. **Graduate Student Training:** CAFS research and technology transfer activities have provided training for numerous graduate students, who have gained applied problem-solving skills using interdisciplinary techniques across multiple scales. As highlighted in this report, graduate students were able to directly interact with forest sector professionals, often in the form of internships, that broaden their perspectives and gave them real-world experience in addition to academic training, which were primarily supported through NSF's INTERN program. Many of these graduate students now work for CAFS IAB member companies or pursued additional educational opportunities.

Highlights

7. **Undergraduate Student Involvement:** CAFS has involved undergraduate students in research activities, exposing them to forest science and encouraging them to pursue additional graduate education. This was primarily accomplished through NSF's Research Experience for Undergraduates (REU) and Skills Training in Advanced Research & Technology (START) programs, which supported four- and two-year students, respectively. REUs were directly involved with CAFS research and actively mentored by faculty, while START grants at NCSU and UM gave exposure to research to associates-level undergraduates, particularly during the busy summer field season. Like graduate students, many of these undergraduates were hired by CAFS IAB member companies or pursued additional educational opportunities.
8. **Technology Transfer:** CAFS facilitated technology transfer between scientists and IAB member personnel, fostering the rapid implementation of new technologies. Given the regional nature of forest management, cross-regional collaboration across CAFS Sites strengthened connections across regions and allow better connections across the sector, particularly data-sharing. Annual IAB meetings, regular communications, and the developed technology roadmap helped to identify existing commonalities, potential synergies, and collaboration opportunities, which led to additional research proposals, new research activities, and collaboration outcomes.
9. **Diverse Workforce:** CAFS has helped increase the diversity of the forestry workforce through aggressive recruiting of graduate students from underserved or underrepresented groups. This was particularly effective with CAFS' two Phase 3 START supplemental grants at NCSU and UM that specifically engaged with two-year technical colleges, which often have higher diversity and underserved populations than more traditional four-year universities. This direct hands-on experience with research fostered new opportunities and exposure to ideas. For example, an NSF START grant with Monroe Community College in highly urban Rochester New York allowed several undergraduates to experience managed forestlands in northern Maine (see article here).
10. **Scientific Community:** CAFS research has benefited the broader scientific community through publications and presentations at national and international meetings. Most importantly, it has supported and helped to strengthen the scientific community of applied researchers at the major forestry universities across the US, which has led to additional collaboration and research outcomes. In addition, the NSF support and emblem of approval has elevated the profile of CAFS research across a broader scientific community beyond the traditional forest sector. Building on this existing collaboration network and the NSF emblem can support future efforts for the sector that leverage this prior investment, strengthen the national profile of the research, and highlight the numerous positive economic, environmental, and societal benefits of well managed forests supported by long-term scientific evidence.

Much of the collaborative effort among the forest product industry in the last 25 years has been focused on promoting legislation for tax efficiency in the emerging landowner category known as Real Estate Investment Trust or Timber Investment Management Organizations. Likewise, many state governments have passed laws that ensure fiscal incentives to retain sustainable family forests from clearing and land-use conversion. CAFS is unique, in that, it constitutes a powerful vehicle for promoting a collaborative scientific effort among the forest products industry and the integration of new research developments into forest management. The focus is nationwide, and it is apparent that the traditional sectors of the forest-based industry, coast-to-coast, share similar challenges. These challenges are related efficient use of fertilization for augmenting productivity, use of new technologies, such as LiDAR for forest sampling and inventory, as well as better models for estimating biomass growth. As a CAFS IAB Executive Committee Chair, I had the pleasure to work with colleagues of the forest-based sector to establish priorities for research topics and evaluate research proposals. I felt that the collective voice of the forest products industry was factored into the CAFS sponsored research and it produced useful results.

John Paul McTague, CAFS Phase 2 IAB Executive Committee Chair

Rayonier

Specific Phase Accomplishments

Phase I (2008–2013)

During Phase I, CAFS was established by its four founding universities (NCSU, OSU, PU, and VT) that was expanded upon, and led to the successfully engagement of several additional universities (AU, UF, UI, UM, UW). CAFS structure, processes, and annual IAB meetings were established in Phase I, which laid the foundation for success in Phase II and III. Significant outcomes across sites was achieved in Phase I, including 518 presentations, 206 publications, and 80 student degrees awarded with 15 CAFS graduates hired by members. CAFS Phase I projects totaled 41, with 7 being multi-site projects. Intellectual property outcomes included one patent application, one patent granted, and 11 inventions producing royalties, given the primary focus on forest genetics and biotech in Phase I.

A supplemental collaborative project (CAFS #10.33) on fundamental research entitled, "Use of Stable Isotopes to Trace the Fate of Applied Nitrogen in Forest Plantations to Evaluate Fertilizer Efficiency and Ecosystem Impacts" (NSF Award #1031473), established direct links between PU, UW, and VT. The project was led by Dr. Tom Fox and focused the use of fertilizer labeled with stable isotopes to determine the uptake and ecosystem fate of fertilizer nitrogen (N) in three of the most important plantation tree species in the US (loblolly pine, Douglas-fir, and black walnut). In addition, the UM site, for example, developed a new forest growth and yield simulator for managed forestlands in the Acadian Region and refined the understanding of how to optimize commercial thinning prescriptions in spruce-fir stands. UM compiled an extensive database of over 4 million observations from existing permanent growth and yield plots to develop an Acadian variant of the Forest Vegetation Simulator (FVS-AD). CAFS' work reduced prediction bias for net stand basal area growth, resulting in substantial financial benefits for Maine's forest industry. Phase I also provided specific recommendations for commercial thinning of spruce-fir stands across northern Maine, leading to increased net present value per acre. These efforts have built synergies and effective partnerships across universities and industry, both internal and external to the regions involved.

Key Accomplishments

- Established CAFS as a collaborative research center with four founding university sites (NCSU, OSU, PU, VT).
- Developed a diverse portfolio of projects across key research areas, including genetics, forest health, growth and yield modeling, wood quality, and forest management.
- Successfully integrated regional research cooperatives under a consistent structure and function.
- Initiated a multi-site collaborative fundamental research effort focused on better understanding tree nutrient uptake following fertilization.

Key Outcomes

- 41 research projects completed
  - 9 on Growth Modeling
  - 10 on Management
  - 3 on Wood Quality
  - 2 on Remote Sensing
  - 13 on Genetics
  - 4 on Forest Health
- 19 MS and 41 PhD graduate students trained
  - 15 hired by IAB industry members
  - 6 hired by non-IAB members
  - 7 hired by IAB government members
- 13 post-doctorate researchers trained
- 206 peer-reviewed publications generated

Key Students

Dr. Rachel Cook was a NCSU PhD student that worked on CAFS Project #CAFS Project 9.14, "Evaluation of the Potential Productivity of Loblolly Pine in Southeastern US using a Twin-Plot Approach across Geological-Climatic Gradients"

Dr. Matt Russell was a UM PhD student that worked on CAFS Project #9.10, "Refinement of Regional Growth and Yield Models for Naturally-Regenerated, Mixed Species Stands in the Northeast"

Dr. Cristian Montes was a NCSU PhD student that worked on CAFS Project #8.01, "Developing Varietal Precision Silvicultural Regimes in Pine and Hardwood Plantations Based on Crown Ideotype"

Rachel Cook
Associate Professor
North Carolina State University

NC STATE UNIVERSITY

Research Interests: Silvicultural management of intensively managed plantation forest systems to enhance long-term productivity and protect natural resources.

Rachel Cook is currently site director for CAFS at NC State University, where she collaborates with industry-led research projects in site productivity mapping.

Rachel's interactions with CAFS research began well before she became a professor at NCSU, when she was working on completing her PhD centered around the effects of intensive plantation forestry on soil carbon as a marker for long-term sustainability. Her research showed that intensively managed plantations were maintaining soil carbon and that there was no real difference in total gains or losses due to plantation species.

CAFS played an integral role in Rachel's professional and academic growth. The annual industry advisory meetings provided an ideal venue to present her research and to network with stakeholders. Before returning to academia, Rachel worked in industry that supports forestry where she was able to gain valuable experience in the private sector. She joined the NCSU faculty in 2016, and in addition to her teaching and CAFS roles, she is Co-Director of the Forest Productivity Cooperative, a university-public-private partnership to better understand site resource management in plantation forestry.

"CAFS provided opportunities for me to connect directly with forest industry and network with stakeholders. These experiences helped define my now current and continued interactions with forest industry as a site director for CAFS."

Arbor Analytics™

Matt Russell
Principal and Lead
Forest Data Scientist,
Arbor Analytics

As a student supported by CAFS, Matt worked on developing a new growth and yield model for the northeastern US. This was novel because few growth and yield models are designed for application in mixed-species stands, which comprise the majority of the forested landscape in the Northeast. Being able to provide tools for practitioners to understand how their forest will change is an essential component of forest management planning, natural capital assessments, and more.

CAFS supported Matt's research and provided him with numerous opportunities to share his regional work with a national audience. This included presenting to national audiences, travel to attend conferences, and research support. "Most important was the dialogue I was able to have with leaders in the forest industry, university researchers, and forest practitioners. Few students are afforded those kinds of opportunities in their graduate programs."

"My involvement in CAFS helped me understand the breadth of the forest industry, the sector my company provides analytical support for today. My involvement in CAFS helped me understand the technical rigor expected in our discipline and the importance of applied research in the forest industry."

Phase I Key Project

CAFS Phase I: Project 10.33

Use of Stable Isotopes to Trace the Fate of Applied Nitrogen in Forest Plantations to Evaluate Fertilizer Efficiency and Ecosystem Impacts

Lead Institutions: University of Washington, Greenwood Resources, Port Blakely Co., Virginia Tech, North Carolina State University, Purdue University

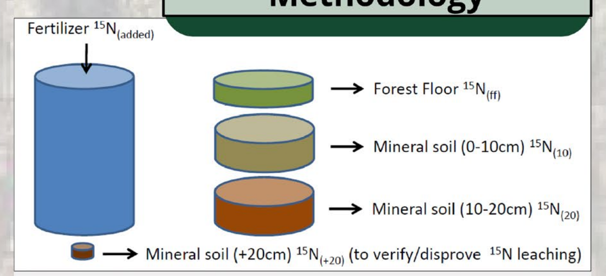
Background and Objectives

Multi-institutional researchers focused on understanding nitrogen (N) uptake and cycling in forest ecosystems after fertilization, with the goal of improving both economic and ecological management. The study used stable isotopes to trace the fate of applied fertilizer N in Douglas-fir, Loblolly Pine, and Walnut forest plantations. Improving the productivity of forest plantations is critical to meet global demand for traditional and emerging wood-based markets. By achieving a better understanding of how fertilizer nitrogen moves through a given system, valuable insights are gained concerning both production and environmental management. The study results provide guidance for adaption of forest management approaches to increase resilience in the face of a changing climate.

Experiment Design

- Regional study sites: Douglas-fir (9 sites), Loblolly Pine (18 sites), & Walnut Plantations (8 sites)
- Sites represent range of soil & stand conditions typical of operational fertilization stands
- Five 100m² circular plots around 1-2 central trees at each location
- Fertilizer treatment randomly assigned
- Ecosystem components (tree, understory, soil) sampled to determine N derived from fertilizer
- Evaluation of different N fertilizer types (urea, polymer coasted urea, MBPT treated urea, MAP coated urea)

Methodology



- » The experiment involved applying ^{15}N-labeled fertilizers to the forest sites in the spring and sampling ecosystem components (study tree, along with soil and forest floor samples) to determine the amount of N derived from the fertilizer.
- » Samples were oven and air dried, followed by course and fine grind of all samples.
- » System components analyzed included tree (foliage, fine branches, coarse branches, bark, growth rings, fine roots), forest floor, litter, shrub stratum, and herbaceous stratum.
- » N, ^{15}N, C, ^{13}C analyzed by isotope-ration mass spectrometry.

Findings

- Enhanced efficiency fertilizers reduced N volatilization losses following fertilization.
- Percent N concentrations increased in all trees with fertilizer treatments. The increase is associated with uptake from applied fertilizers.
- This research project increased our knowledge of the fate of applied N and the fundamental processes controlling N transformations in forest ecosystems and will help guide efficiency and optimization of fertilizer use in forests.

Outcomes

J.E. Raymond. 2016. Use of Stable Isotopes to Trace the Fate of Applied Nitrogen in Forest Plantations to Evaluate Fertilizer Efficiency and Ecosystem Impacts. PhD diss., North Carolina State University.

J.E. Raymond, T.R. Fox, B.D. Strahm, & J. Zerpa. 2016. Ammonia volatilization following nitrogen fertilization with enhanced efficiency fertilizers and urea in loblolly pine (*Pinus taeda* L.) plantations of the southern United States. *Forest Ecology & Management* 376: 247-255. http://dx.doi.org/10.1016/j.foreco.2016.06.015

J.E. Raymond, T.R. Fox, & B.D. Strahm. 2016. Understanding the Fate of Applied Nitrogen in Pine Plantations of the Southeastern United States Using ^{15}N Enriched Fertilizers. *Forests* 7: 270. doi:10.3390/f7110270

S. Michelsen-Correa, R. Harrison, & C. Dietzen. 2018. Enhanced efficiency fertilizers (EEFs) do not increase nitrogen retention in Pacific Northwest Douglas-fir forest soils four weeks post-fertilization. *Forest Ecology & Management* 427: 317-324. https://doi.org/10.1016/j.foreco.2018.06.010

J.L. Sloan, F.K. Salifu, & D.F. Jacobs. 2021. Nitrogen Recovery from Enhanced Efficiency Fertilizers and Urea in Intensively Managed Black Walnut (*Juglans nigra*) Plantations. *Forests* 12: 352. doi.org/10.3390/f12030352

Phase II (2013-2018)

During Phase II, CAFS continued to build upon the foundation laid in Phase I, achieving a number of significant outcomes and accomplishments across its various sites. CAFS Phase II saw the initiation of 25 research projects, a figure comparable to Phase I, with 36% of these being multi-site collaborations. These projects trained 159 students, along with 6 post-doctoral researchers, demonstrating a strong commitment to developing future talent for the forest sector. Productivity in Phase II was either comparable to or higher than Phase I in most respects, particularly in the number of graduate students trained. CAFS publications totaled 292 peer-reviewed publications, a vast majority (88%) of which were co-authored by a graduate student. The IAB played a stronger role in shaping the research focus of Phase II, recommending the maintenance of the original four research focal areas—genetics, growth & yield modeling, forest health, and forest management—while putting emphasis on strengthening future wood quality research and remote sensing efforts. This consistency in research areas facilitated several multi-site and multi-year field/laboratory collaborations.

A multi-site collaborative research effort focused on understanding competition processes in contrasting forest types involved the UM, UW, and VT sites, which led to the development of new methodologies for representing competition in forests that were incorporated into growth and yield models. The UM CAFS site continued to improve decision-support tools and commercial thinning prescriptions in the Acadian forest of northern New England. Specific objectives for UM included developing growth and yield predictions for diverse genotypes and silvicultural practices, extending the Acadian Variant of the Forest Vegetation Simulator (FVS-ACD) to managed stands in the Northeast US, and enhancing the understanding of individual-tree responses to commercial thinning. UM's expertise in remote sensing also grew significantly, with the establishment of the Barbara Wheatland Geospatial Analysis Laboratory and key faculty appointments in remote sensing, which was better leveraged in Phase III of CAFS.

Phase II aimed to build upon the successes of Phase I by applying CAFS expertise to address problems with targeted, applied, and collaborative research coordinated across multiple university sites. The overarching vision was to support the US forest sector by optimizing genetic and cultural systems to produce high-quality raw forest materials for new and existing products. CAFS leveraged the resources of individual sites and maintained an efficient organizational structure to meet five core objectives, including serving as a national organization for R&D, coordinating nationally relevant research activities, documenting and communicating research outcomes, providing a long-term strategic vision for the IAB, and creating national networking opportunities.

Key Accomplishments

- Expanded CAFS to nine university sites, adding regional depth and breadth.
- Continued regional integration of research projects and completed a second multi-site collaborative fundamental research effort.
- Maintained a balance across research focal areas, including forest management, genetics, and growth and yield modeling.
- Need to strengthen wood quality research and shifting towards more remote sensing was emphasized by IAB for the Phase III research agenda.

Key Outcomes

- 25 research projects initiated:
  - 6 on Growth Modeling
  - 11 on Management
  - 5 on Genetics
  - 3 on Forest Health
- 159 students trained
  - 36 BS
  - 77 MS
  - 46 PhD
- 6 post-doctorate researchers trained
- 292 peer-reviewed publications generated

Key Students

Patrick Clune was an UM MS student that worked on CAFS Project #10.32, "Examining the influence of precommercial and commercial thinning in balsam fir and red spruce stands across Maine" that was led by UM's Drs. Robert Wagner and Aaron Weiskittel

Dr. Andrew Nelson was a UM PhD student that worked on CAFS Project #12.38, "Extending the Acadian Variant of the Forest Vegetation Simulator (FVS) to Managed Stands in the Northeast US"

Patrick Clune
Forest Analyst/Biometrician
Roseburg Resources Company

Patrick Clune had the opportunity to get involved with CAFS-supported research while a master's student at the University of Maine in 2010. CAFS supported his analysis on two commercial thinning studies in Maine's spruce-fir forests. In the late 1990s and early 2000s there were millions of acres of two common conifer stand types reaching merchantability in Maine after the spruce budworm devastation of the 1970s and 1980s. There were dense, older red spruce dominated stands that were still intact after being missed by the spruce budworm and young balsam fir dominated stands that regenerated after spruce budworm related mortality that were precommercially thinned in the late 1980s and 1990s. Pat analyzed the first 10 years of growth response in these studies. This research was important to gain an understanding of how these stand types would respond from commercial thinning treatment, and if thinning could be a viable tool in the forest management toolbox. Although Maine has a long and rich history in forest management, these were the first thinning studies in the state.

"CAFS helped me as a student with exposure to the data and analysis needs of the timber industry. I was able to learn new and useful techniques for analyzing large datasets that those in the sector were interested in. The feedback I received from industry cooperators was quite valuable in refining my approach to forest analytics."

After graduating, Pat gained industry experience as a biometrician and forest analyst with CAFS members Weyerhaeuser, Campbell Global, and Hancock Forest Management.

In his current role as Forest Analyst/Biometrician at Roseburg Resources Company for the Pacific Northwest region, CAFS continues to support Pat with new applied research that he can use to improve the timber inventory for his company. One particularly interesting area of research that CAFS has been innovating in across multiple regions is Small Area Estimation: "I think there is a lot of interest from industry cooperators in what gains can be made integrating Small Area Estimation techniques into inventory systems."

CAFS project 10.32. Examining the influence of precommercial and commercial thinning in balsam fir and red spruce stands across Maine.
Project Lead: Dr. Robert Wagner, University of Maine.

Dr. Andrew Nelson
Associate Professor,
University of Idaho

Andrew Nelson worked on a CAFS project as a PhD student at the University of Maine, which he completed in 2013. The research used annual measurements of growth and yield of various conifer and hardwood species in naturally-regenerated mixedwood stands that were part of the Silvicultural Intensity and Species Composition Experiment (SICOMP) on the Penobscot Experimental Forest. That research used the data to fit new biomass models for small trees and validate aboveground biomass models used by the USDA Forest Service Forest Inventory and Analysis Program at the time. The findings suggested the FIA methods considerably underestimated biomass of small trees in the Northeast. The model validation occurred at a time when considerable effort was underway to develop new methods to estimate tree biomass for the FIA program. This research was critical for bringing attention to saplings, which are widely common across the Northeast during early stages of forest development.

CAFS was critical for my professional development as a student and when I entered the workforce. While at the University of Maine, CAFS provided a forum to meet with site leads, industry professionals, and other students to build my collaborator network. The CAFS model that brings researchers and industry together is something I have emulated with my research program since first starting as a university professor in 2013. My research program is highly applied and collaborative with various industry partners. CAFS taught me how to effectively communicate with industry to understand their needs and then use those conversation to develop research objectives and methods to generate research findings that can help influence forest management.

Andrew is currently the Tom A. Alberg and Judith Beck Endowed Chair for Native Plant Regeneration and Associate Professor at the University of Idaho. In this role, he serves as the Director of the Center for Forest Nursery and Seedling Research and Franklin H. Pitkin Forest Nursery, the state nursery of Idaho. CAFS support has provided an opportunity to collaborate with researchers at other sites to study problems critical for the success of reforestation across the United States. Our current project is examining the potential benefits of drought conditioning of nursery seedling to improve outplanting success in Indiana, Idaho, and Oregon.

CAFS Phase II: Project 15.64

Does Commercial Thinning Improve the Growth Response and Upper Diameter Distribution Potential of Forest Stands?

Lead Institutions: University of Maine, Virginia Tech, University of Washington

NSF Award # 1539982

Background and Objectives

In this collaborative project, scientists across three of the most important forest types (loblolly pine, Douglas-fir, spruce-fir) in the United States linked a variety of long-term datasets and advanced statistical techniques to better understand tree competition. These data cover contrasting conditions that included unthinned/thinned, mixed species, and naturally regenerated/planted, which allows for more comprehensive comparisons. Study results provide a more complete understanding of and better quantitative expressions for competition effects on tree and stand growth and survival. this research illustrated one of the core issues facing forests and the value of long-term research in addressing these issues by increased reliability of decision-support tools for predicting future forest growth and yield.

Experiment Design

Long-term data was synthesized and analyzed for the three most important North American softwood forest types:

- Shade-intolerant planted loblolly pine (*Pinus taeda* L.) of southeastern US
- Mid-tolerant planted Douglas-fir (*Pseudotsuga menziesii* Mirbel) of Pacific Northwest US
- Tolerant naturally regenerated red spruce-balsam fir (*Picea rubens Sarg* & *Abies balsamea* (L.) Mill.) of northeastern US

Methodology

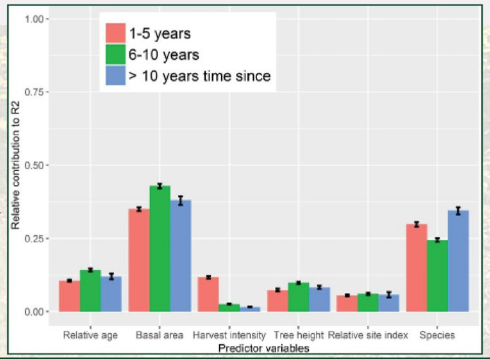
» Contemporary statistical techniques and computing technology were used to gather information from forestry field studies to develop improved quantitative measures of tree- and stand-level competition in response to thinning in terms of relative volume growth or understanding the maximum growth potential and its association with species.

» Silvicultural systems varied from intensively managed even-aged plantings of single species to extensively managed uneven-aged mixed species stands.

» Synthesis of data lead to more complete understanding of the fundamental processes involved.

Findings

- Shade-tolerant spruce-fir can positively respond to thinning treatments even after 70 years of age.
- Forest managers need to consider that shade-intolerant species like loblolly pine and moderately shade-tolerant species like Douglas-fir likely reach maximum growth potential much earlier than shade-tolerant species.
- Thinning treatments should be applied earlier for a stand of shade-intolerant species than for a stand of shade-tolerant species.
- Surviving stems in these stands may pass a period of growth shock, which resulted a reduced annual growth during initial years since thinning.



Relative importance of predictor variables for relative volume growth (relative to previous year) of residual trees following commercial thinning treatments (data from unthinned plots excluded from analysis) of four softwood species. Bars represent means with 95% confidence intervals obtained from 1000 bootstrap replications.

Outcomes

Bose, A.K., Weiskittel, A., Kuehne, C., Wagner, R.G., Turnblom, E., and Burkhart, H.E. 2018. Tree-level growth and survival following commercial thinning of four major softwood species in North America. Forest Ecology and Management 427: 355-364.

Bose, A., Weiskittel, A., Kuehne, C., Wagner, R.G., Turnblom, E., and Burkhart, H.E. 2018. Does commercial thinning improve stand-level growth of the three most commercially important softwood forest types in North America? Forest Ecology and Management 409: 683-693.

CAFS Phase II: Project 16.65

Understanding and Modeling Competition Effects on Tree Growth and Stand Development Across Varying Forest Types and Management Intensities

Lead Institutions: Virginia Tech, University of Maine, University of Washington

NSF Awards # 1539982, 1539982, 1534751

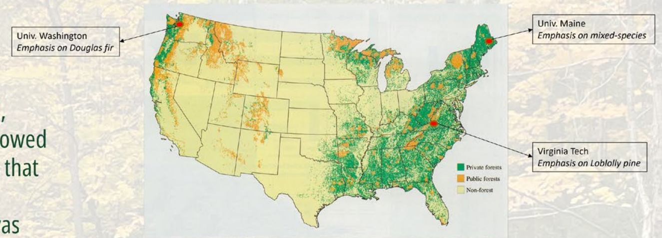
Background and Objectives

In this multisite-industry (Rayonier, J.D. Irving, Campbell Group) collaborative project, contemporary modeling and statistical techniques and computing technology were used to extract information in forestry field studies to develop improved quantitative measures of tree- and stand-level competition. Researchers addressed questions of whether incorporation of spatially explicit information improves predictions when compared to spatially implicit measures of competition, whether maximum size-density relationships provide consistent implied values or basal area carrying capacity, do climatic influences affect competition and mortality relationships, and does genetic variability of trees in stands alter competition relationships.

Experiment Design

Silvicultural systems varied from intensively-managed even-aged plantings of single species to extensively-managed uneven-aged mixed species stands across 3 sites.

- Compile data sets
- Develop and evaluate alternates measures of tree and stand level competition
- Build on initial analyses on quantifying and mapping spatial heterogeneity in loblolly pine with additional analyses in Douglas fir and western hemlock
- Acquire additional data on competition relationships in seedling and variatal stands of loblolly pine



Findings

- When individual tree growth equations were fitted, competition indices that included tree locations showed only marginal improvement in accuracy over those that did not use spatial information.
- A spatially explicit metric of solar radiation input was found to be highly correlated with Douglas fir diameter growth, but after incorporating relative tree size metrics and stand-level spatially-implicit stand density measures, the strength of the correlation dropped significantly.
- A diameter-based relative spacing measure of stand density produced good results when deriving implied basal area carrying capacity for loblolly pine.
- An analysis aimed at quantifying and mapping microsite variability in loblolly pine plots found methods from numerical ecology to be successful in some, but not all instances.
- Climate effects on mortality relationships were difficult to detect and model.
- After accounting for distance to and size of competitors, genotype did not appear to have a strong influence on competition relationships.

Methodology

» Contemporary statistical techniques and computing technology were used to gather information from forestry field studies to develop improved quantitative measures of tree- and stand-level competition in response to thinning in terms of relative volume growth or understanding the maximum growth potential and its association with species.

» Silvicultural systems varied from intensively managed even-aged plantings of single species to extensively managed uneven-aged mixed species stands.

» Synthesis of data lead to more complete understanding of the fundamental processes involved.

Outcomes

Bose, A.K., Weiskittel, A., Kuehne, C., Wagner, R.G., Turnblom, E., and Burkhart, H.E. 2018. Tree-level growth and survival following commercial thinning of four major softwood species in North America. Forest Ecology and Management 427: 355-364.

Bose, A., Weiskittel, A., Kuehne, C., Wagner, R.G., Turnblom, E., and Burkhart, H.E. 2018. Does commercial thinning improve stand-level growth of the three most commercially important softwood forest types in North America? Forest Ecology and Management 409: 683-693.

Kuehne, C., Weiskittel, A., and Waskiewicz. 2018. Comparing performance of contrasting distance-independent and distance-dependent competition metrics in predicting individual tree diameter increment and survival within structurally-heterogeneous, mixed-species forests of Northeastern United States. Forest Ecology and Management 433: 205-216.

Phase III (2019-2025)

During Phase III, CAFS aimed to rebuild capacity given the short pause between phases, change in leadership (both at the center- and site-levels), and NSF's expectation of long-term sustainability following graduation. This was attempted by building on its previous phases by increasing cross-regional synthesis or integration of research efforts, maintaining a nationally relevant focus, and engaging with new faculty or IAB members. **An important first step of Phase III was developing a member-driven, cross-cutting technology roadmap** that facilitated collaboration, innovative research, and set the stage for future sustainability (Figure 12). A key focal area of the technology roadmap was to leverage emerging technologies and approaches in forestry, such as LiDAR, unmanned aerial vehicles (UAVs), site potential productivity assessments, and forest health risk assessment, to create a common research platform across regions. This phase emphasized collaborative applied research coordinated across multiple university sites. CAFS Phase III had five core objectives:

1. Serve as a national organization for R&D relevant to the forest industry
2. Coordinate and conduct nationally-relevant research activities across multiple sites that align with the prioritized needs of the forest industry
3. Document and communicate key research outcomes to relevant partner organizations
4. Provide a long-term strategic vision for the research needs of the Industrial Advisory Board (IAB)
5. Create national networking opportunities for universities and industry

A striking statistic is that the CAFS' robust Phase III research portfolio now has 27 active projects, which aligned with a peak of projects during Phase II (2013), despite having a lower number of participating university sites in Phase III. **Over 70% of the Phase III projects involve multiple university sites, versus less than 20–25% of projects in Phases I and II.** This shift highlights the highly collaborative nature of the involved universities, IAB membership and the importance of cross-regional efforts, all of which are critical for the long-term sustainability of CAFS. The original intent of CAFS was to build synergies and effective partnerships across universities and industry both internal and external to the regions involved, which was fully realized in Phase III with a solid foundation for future efforts related to CAFS.

As highlighted below, there are several recent examples of highly successful cross-regional, multi-site projects undertaken by CAFS in Phase III. **These efforts have clearly demonstrated their ability to generate valuable research outcomes with a direct impact on forest management practices.** By leveraging the unique expertise of multiple university sites and IAB partners, CAFS has effectively addressed national and regional forestry challenges, contributing to the sustainability and productivity of the nation's forests. In the later years of Phase III, CAFS leadership recognized the need to strategically shift focus on long-term sustainability. A multi-tier strategy to help

Phase III Research & Technology Roadmap

	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Outcomes
Theme 1: Forest Modeling & Decision-Support Tools **Primary IAB Partners: American Forest Management, Green Diamond, and Campbell Global**						**Provide IAB members with improved tools that allow better and more precise forest management and planning**
Project 1: Assessing and mapping regional variation in potential site productivity Lead Partners: NCSU, UI, UGA, UW, PU	■	■	■			Better understand how potential site productivity differs across the key forest regions in the US, the most influential factors, and produce high-resolution maps for IAB members to aid planning
Project 2: Assessing and mapping regional variation in site carrying capacity Lead Partners: UI, UM, OSU, VT, UGA, UW	■	■	■			Derive consistent estimates of maximum stand density index, evaluate most influential factors, and provide high-resolution maps to aid management
Project 3: Evaluation and refinement of regional GY models Partners: UM, VT, UGA, OSU, PU			■	■	■	Using the outcomes from Projects 1 and 2, evaluate regional growth and yield behavior and refine as possible
Theme 2: Effective Use of Remote Sensing Technologies **Primary IAB Partners: JD Irving, Rayonier, and Weyerhaeuser**						**Evaluate and leverage emerging remote sensing technologies to improve planning**
Project 4: Mapping species composition and past disturbance using optical sensors Partners: UI, UM, UGA	■	■	■			Optimal sensors like Landsat and Sentinnel-2 offer the ability to annual map species composition and past disturbance, but have yet to be tests across the US
Project 5: Improving efficiency and accuracy of Enhanced Forest Inventories derived from LiDAR Partners: UW, OSU, UGA, UM	■	■	■	■	■	LiDAR is becoming increasingly used to produce Enhanced Forest Inventories, but uncertainties on ground data, necessary metrics, and modeling method remain.
Project 6: Using hyperspectral imaging to evaluate forest health risk Partners: VT, NCSU, OSU, UM			■	■	■	Forest health risks are extensive and difficult to detect. Hyperspectral imaging from terrestrial and/or airborne sensors can help detection and quantification
Theme 3: Improved Silvicultural Practices **Primary IAB Partners: Hancock Forest Management, International Forest Company, and Molpus Timberlands**						**Forest managers have a variety of silvicultural regimes to select from, but it is often unclear on selecting the best practices for each site**
Project 7: Quantifying long-term gains using advanced genetics Lead Partners: PU, UGA, OSU, NCSU	■	■				Tree genetics has seen significant advances in recent years due to better breeding practices and cloning, but a synthesis of the long-term potential effects of these practices across multiple species has yet to be presented
Project 8: Modeling forest response to early stand treatments Lead Partners: UI, UW, NCSU, VT	■	■	■	■	■	Vegetation management is critical to successful rotations, but its prediction is complicated by a variety of factors such as the type and extent of competing vegetation. Leveraging long-term datasets, the outcomes of contrasting treatments would be assessed and modeled.
Project 9: Identifying type and level of response to forest fertilization Lead Partners: UW, UI, NCSU, PU			■	■	■	Forest fertilization is a widely used silvicultural practice that is difficult to predict. Using long-term and newly available data, methods to improve predictions of forest responsiveness would be evaluated.

Figure 12. *CAFS Phase III Technology Roadmap initiated with 2019 NSF proposal and refined in recent years.*

sustain CAFS, addressing a mechanism to centralize center funding, facilitate and encourage university participation, secure and significantly leverage IAB member contributions, and retain critical benefits of participation. This strategy involved:

- Continuing to recruit new members, particularly foundations
- Seeking private support
- Federal research grants and contracts.
- Exploring international memberships and partnerships
- Direct site contributions

By 2024, CAFS entered its final year of NSF support. IAB member and researcher collaboration and engagement remained high, with continued incorporation of advanced & emerging technologies, and synthesis of regional datasets. CAFS effectively demonstrated the ability and importance of multi-site, cross-disciplinary research in Phase III. A key consideration was the need to strategically shift focus on long-term sustainability.

Key Accomplishments

- Greater focus on nationally-relevant research projects
- Reorganized research focal areas into three primary themes: forest management, remote sensing, and decision-support tools
- Shifted greater focus towards remote sensing
- Strengthened collaboration with national organizations, such as NCASI
- Developed an online GIS interface for CAFS data and spatial products (Figure 13)
- Partnered with NCASI's Partnership for Small Area Estimation to cost-share

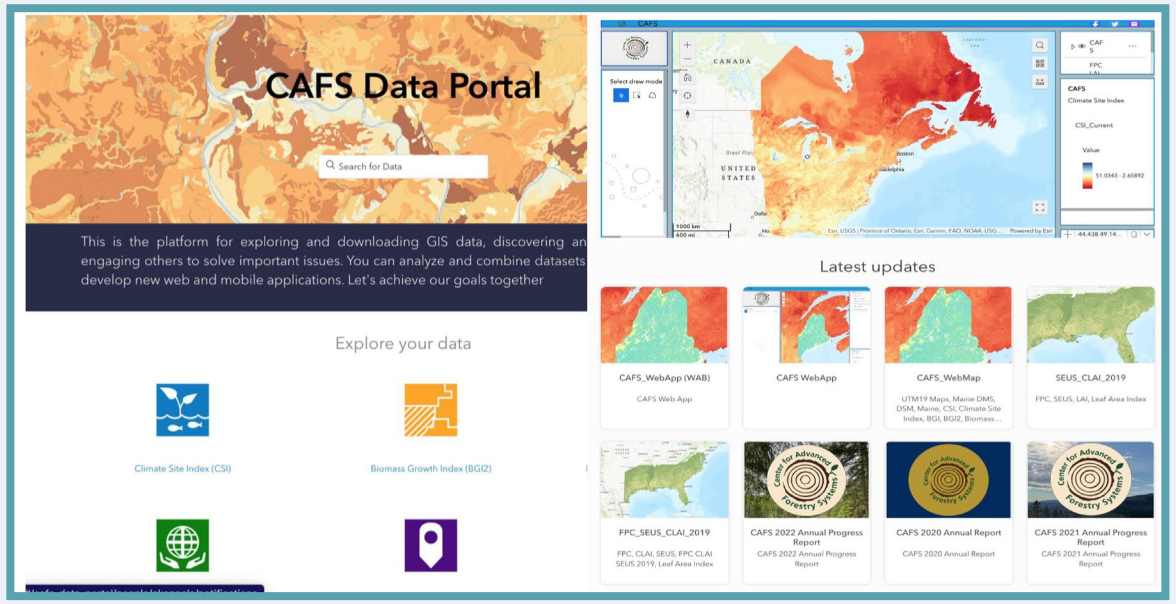


Figure 13. *CAFS Online Data Portal developed by Dr. Okan Pala of North Carolina State University during Phase III.*

several IAB member approved and involved projects:

- **23.104,** "The Interplay between Sampling Design and Small Area Estimation to Improve Timberland Inventory" led by Dr. Temesgen of OSU.
- **24.105,** "Robust small-area estimation strategies for developing accurate stand-level diameter distributions" led by Dr. Poolakkal of UI.
- **24.106,** "Integrating SAE methods with stand-level forest inventory and growth projection for southern pine plantations" led by Dr. Yang of UGA.
- **24.107,** "Using Small Area Estimation and 3D-NAIP/Sentinel-derived Variables for Multivariate Prediction of Stand Attributes" led by Dr. Joo of OSU.

Key Outcomes

- Development of a strategic plan and technology roadmap for CAFS.
- 32 research projects in progress or completed
  - 1 on Forest Health
  - 3 on Genetics
  - 3 on Growth Modeling
  - 11 on Management
  - 13 on Remote Sensing
  - 1 on Wood Quality
- High level of cross-regional, multi-site collaboration (>70% of projects).
- Continued training of students and post-doctoral researchers.
  - 25 BS
  - 41 MS
  - 20 PhD
  - 5 Post-docs
- Successful applications for supplemental funding opportunities, including REU, INTERN, and START grants.
- 178 publications
- 67 peer-reviewed publications
- 37 CAFS students hired by IAB member companies

Key Students

Haley Anderson is a PhD student with Dr. Mark Kimsey at UI working on CAFS Project #23.101, "Site-stand dynamics and pine beetle mortality in ponderosa pine ecosystems."

Lila Beck is a MS student with Dr. Michael Premer of UMaine and an NSF INTERN working with Dr. Julio Rojas of Weyerhaeuser on CAFS Project #23.100, "Use of carbon isotopes for assessing tree response to thinning."

Haley Anderson
PhD Candidate
University of Idaho

Research Interests: Climatic, edaphic, physiographic and mensurational stand drivers of western pine beetle infestation and ponderosa pine mortality for the purpose of modifying SDImax management guidelines

Haley Anderson is currently working to complete her PhD studies at the University of Idaho, with an anticipated graduation date of May 2026.

Haley is working with Dr. Mark Kimsey focusing her research on site-stand dynamics and pine beetle mortality in ponderosa pine ecosystems.

"My involvement with CAFS has allowed me the opportunity to not only network with folks from all over, but also to learn about interesting research projects and emerging technologies in forestry. It has been an immensely positive and rewarding experience."

Her dissertation is tentatively titled "Ponderosa pine-killing bark beetles: Hazard models for the past, present and future," which no doubt may be refined as the rest of the dissertation comes together.

After graduating, Haley hopes to continue working in Dr. Kimsey's lab at the University of Idaho on a post doc. Following that, she is eager to apply for research positions with the Forest Service Research Stations in the intermountain west.

Lila Beck
MS Candidate
University of Maine

Lila Beck is currently working to complete her MS degree at the University of Maine, with an anticipated graduation date of August 2025. The working title of her master's thesis is "Secrets in the CTRN."

Lila is working with Dr. Mike Premer of UMaine conducting research on the commercial thinning research network (CTRN) on the commercial forests of northern Maine. Her MS work utilizes CTRN data to evaluate long-term implications of commercial thinning on species diversity and community composition of natural regeneration. Additionally, she will be building off previous work using CTRN data to model NPV under different scenarios.

"Through my CAFS internship with Weyerhaeuser I'm working on building a R Shiny app that can be used to aid in PCT decision making processes. Through CAFS, I have been able to connect with industry professionals in a meaningful way. My internship experience in particular has given me an opportunity to shadow foresters, gain hands-on collaboration experience, and has been an overall amazing opportunity for me."

Lila was awarded an NSF INTERN to work with Dr. Julio Rojas of Weyerhaeuser on CAFS Project #23.100: "Use of carbon isotopes for assessing tree response to thinning."

After graduating, Lila plans to start work on her PhD at UMaine.

Phase III Key Projects

CAFS Project 19.75
Assessing & Mapping Regional Variation in Site Productivity

*Rachel Cook (NCSU), Cristian Montes (Rayonier), Aaron Weiskittel (UM),
Jeff Hatten (OSU), Mark Coleman (UI), Doug Jacobs (Purdue), Mark Kimsey (UI),
Doug Maguire (OSU), Kim Littke (UW)*

Background and Objectives

One of the primary determinants of optimal management practices is the potential site productivity, which influences the growth and development of forests. This project features cross-site collaboration and sharing of remotely sensed and empirical field data for spatial modeling of potential site productivity. The objective is to develop a consistent and biologically-meaningful metric of potential site productivity that can be related to a combination of environmental and edaphic factors and mapped across the various regions.

Experiment Design

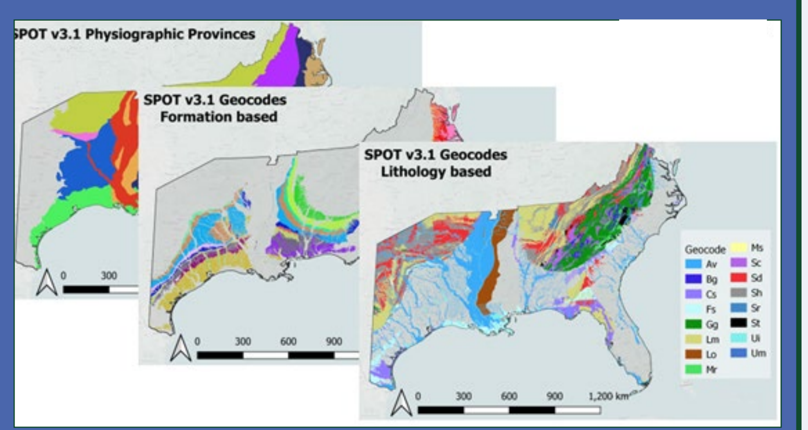
- Site Productivity Optimization of Trees: SPOT
- Collected USGS data across southeast US for large-scale site index mapping
- Develop web-based interface

Methodology

- Look for "gaps" in actual v. potential productivity
- Incorporate satellite/drone LAI to refine predictions/productivity modeling
- Continent-scale C budget under varying scenarios

Outcomes

- Northwest regional SDImax models are being shared (web apps and rasters).
- SDImax model built for loblolly pine in the southern United States, sensitive to site, stand, and silvicultural treatments, and validated by local experts.



Impact

This project has contributed to a consistent methodology for identifying and managing forest density across multi-regional land holdings, improving forest management practices.

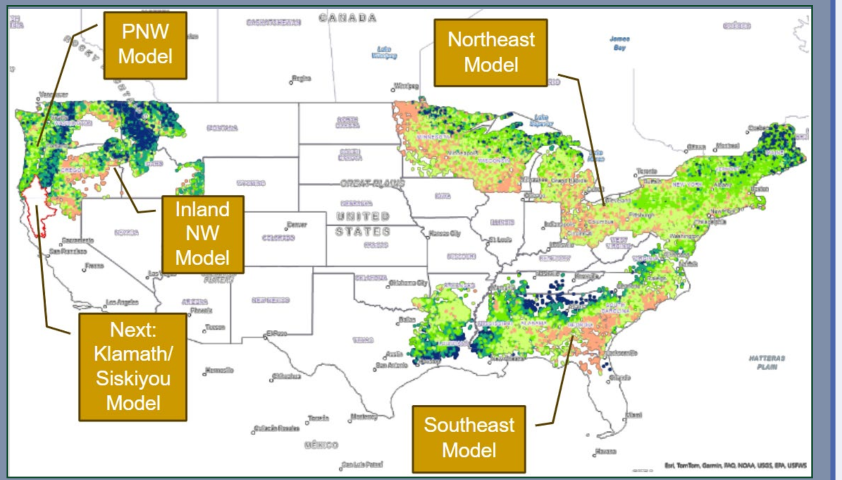
Phase III Key Projects

CAFS Project 19.76
Assessing & Mapping Regional Variation in Site Carrying Capacity Across the Primary Forest Types in the US

*Mark Kimsey (UI), Aaron Weiskittel (UM), Rachel Cook (NCSU), Cristian Montes (Rayonier),
Doug Mainwaring (OSU), Eric Turnblom (UW)*

Background and Objectives

Maximum site carrying capacity determines the number of individuals of a certain size per unit of area that a defined stand can support and maintain. The objectives of this research project are to 1) synthesize a nationwide forest measurements database from publicly available data and from CAFS members, 2) standardize maximum carrying capacity modeling, and 3) create efficiencies for multiregional forest management organizations via species-site spatial models of SDImax for commercial species.



Experiment Design

- Datasets: 543,249 inventory plot records supplied by CAFS members and the USFS FIA program, spatially associated with >200 physiographic variables
- Analysis: Robust machine learning models applied across major US regions to relate key forest growth factors to maximum carrying capacity

Outcomes

- Robust regional forest carrying capacity models for major US conifer species developed for the Northwest, Northeast, and Southeast US.
- Web application and Python-based script developed for CAFS members to operationally deploy model outputs in silvicultural decision support systems.
- Machine learning models capable of identifying current key growth drivers of carrying capacity at the stand scale, but regionally robust.
- Identified scale at which projected climate shifts will impact forest carrying capacity in Northwest forests (~5–20% reduction).

Impact

This project has contributed to a consistent methodology for identifying and managing forest density across multi-regional land holdings allowing for species and silvicultural treatment optimization.

Phase III Key Projects

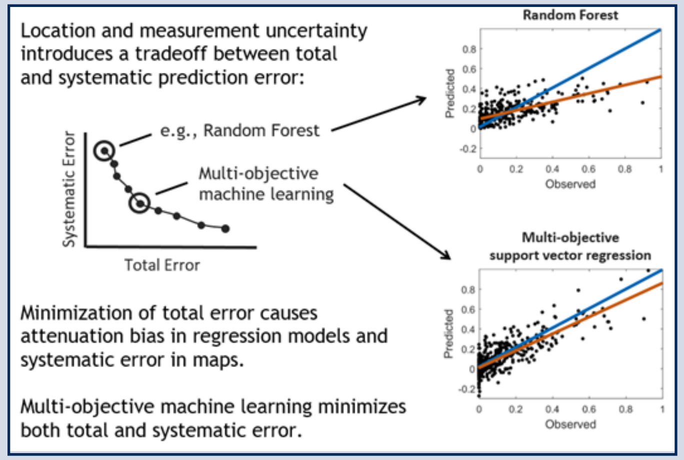
CAFS Project 20.79

Multi-Regional Evaluation of New Machine Learning Algorithms for Mapping Tree Species Distribution and Abundance

Kasey Legaard, Aaron Weiskittel,
Ken Bundy, Erin Simons-Legaard (UMaine)

Background and Objectives

This research specifically targets the problem of eliminating systematic map error using a ML method that is capable of minimizing both total and systematic error in satellite-derived maps. This mapping approach combines the strength of Support Vector Machines (SVMs) to model complex, nonlinear relationships based on limited training data, a common condition in forestry applications, with the adaptability of a multi-objective Genetic Algorithm (GA).



Experiment Design

- Statewide image processing (300+ Sentinel-2 images)
- Species and forest types mapping across northern Maine; followed by the remainder of the state
- Improve the effective resolution of species maps by modifying the production code
- Integrate newly developed forest maps with spruce budworm monitoring data to test for associations between forest conditions and population trend
- Develop and test a prototype cloud-hosted geospatial database application to enable borderless, un-tiled raster data processing for large forest mapping project

Outcomes

- Species and forest type mapping workflows tested and finalized across approximately 5 million acres.
- Currently processing data for statewide coverage.
- Plan to integrate with NOAA C-CAP data and deliver final land cover products.
- Preliminary aboveground live biomass from NAIP point cloud metrics and Sentinel-2 bands.

Impact

This project has continued the development and proof of concept of low-cost forest mapping methods, improving the accuracy and efficiency of forest mapping.

Future Pathways

CAFS has completed its third and final phase of the NSF IUCRC with full graduation in December 2025. CAFS will remain a graduated IUCRC within the broader NSF portfolio and can continue to use the NSF emblem. **CAFS has unique value proposition given its national focus, science synthesis mission, and network of applied scientist and practitioners across the US and sector** (Figure 14). CAFS leadership and IAB are continuing to explore options to sustain the program following its graduation. Currently, a multi-faceted approach has been proposed, which includes centralizing a portion of university site resources, seeking additional new members with national interests, and pursuing additional grants and contracts. Given the US forest products industry faces unprecedented challenges, including environmental uncertainty, evolving markets, technological disruptions, and increased pressure for sustainable practices, CAFS fills a critical gap by providing a national platform for collaborative, use-inspired research that individual companies or regional cooperatives cannot achieve alone (Figure 15). The need for CAFS has grown more urgent as Federal funding for forest-related research has declined dramatically in recent decades and is expected to decline even more sharply going forward. CAFS' unique ability to address these multifaceted, cross-regional issues positions it as an essential resource for the sector's future innovations, competitiveness, and sustainability.

Conclusion

CAFS has made significant contributions to the advancement of forest applied science, practice, and management. With unique direct long-term support from NSF, the program has effectively leveraged the expertise of multiple university sites and IAB partners to address national and regional forest management challenges. CAFS research has led to increased forest productivity, enhanced competitiveness of the US forest products sector, and the development of improved decision-support tools for forest managers. The program has also fostered the development and implementation of new technologies in the forest and promoted sustainable forestry practices through robust, use-inspired science. This report highlights the dramatic and continual evolution of CAFS across the three 5-year phases. CAFS started with four universities and 68 IAB members that grew to over nine universities and 120 IAB members at its peak in Phase II. Today, CAFS remains strong with seven universities and over 50 IAB members with room to grow. Consequently, CAFS' long history, continued relevance, and current momentum make it well-positioned to continue its important work in the years to come.

> CAFS has always been a forum where members of industry, academia, and the broader scientific community could come together to exchange ideas and establish meaningful collaborative bonds. The community has actively developed many of the leaders of our industry and forest science. Compared to many other industries ours is small and resources scarce. CAFS provides a national forum to amplify needs and escalate resources to prevent duplication of efforts at regional scales. From an industrial perspective, we now can adapt this network to prioritize the most significant scientific challenges and continue to groom the leaders of tomorrow through exposure on solutions today.
>
> *Nathaniel Naumann, CAFS Phase 3 IAB Executive Committee Chair*
>
> PotlatchDeltic

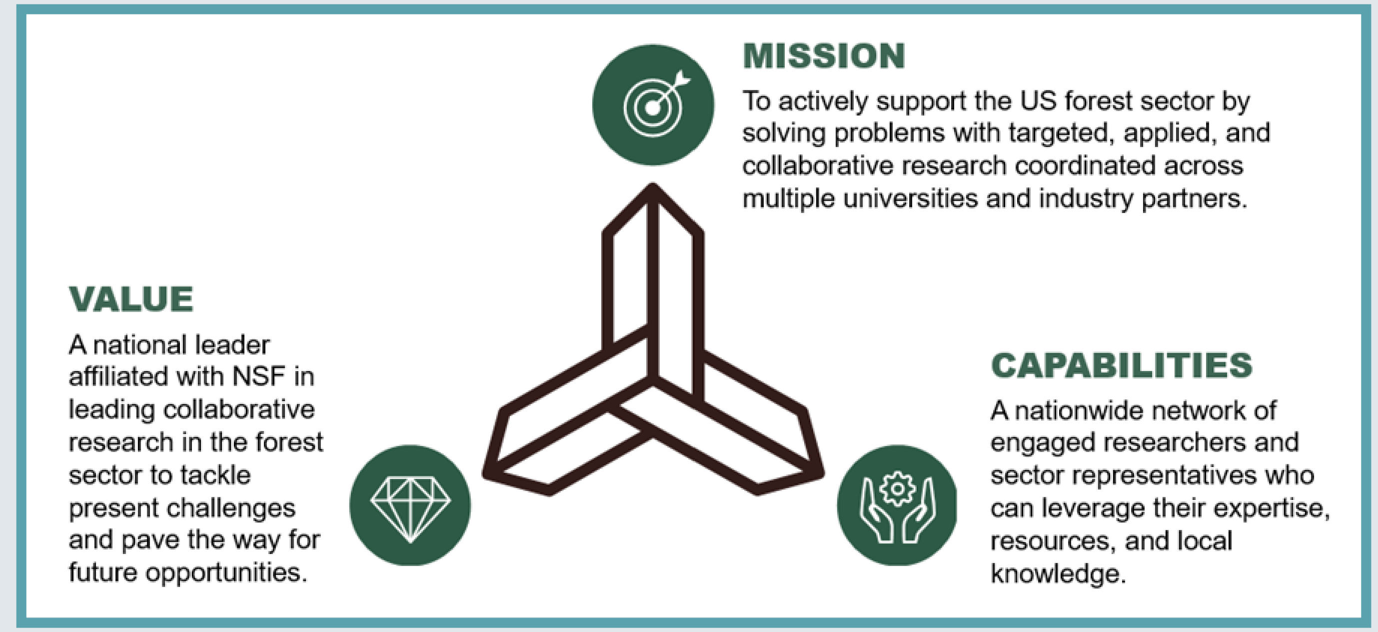


Figure 14. *CAFS unique value proposition that links its vision, mission, and unique capabilities.*

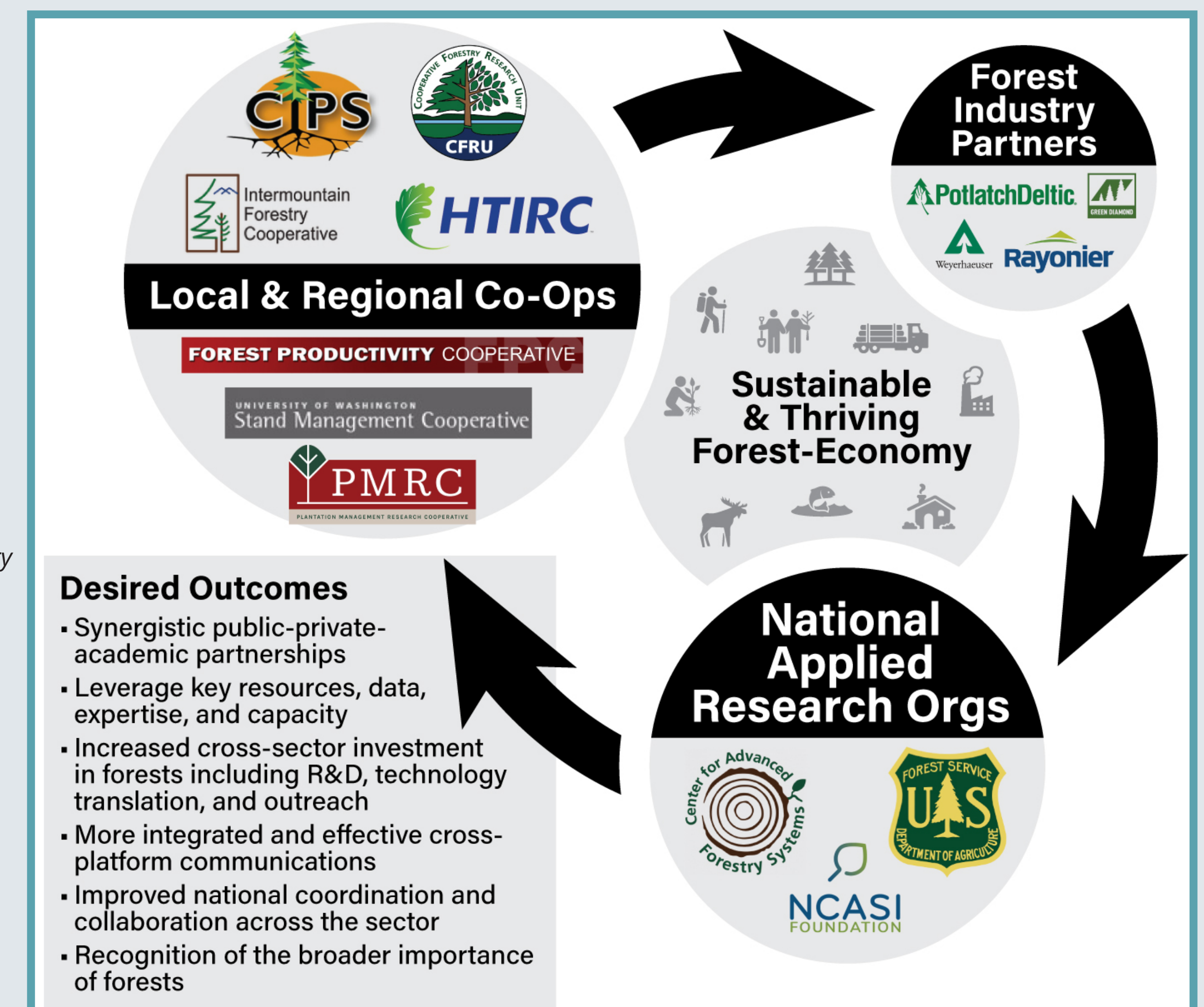


Figure 15. *Future vision and relevance for a national R&D consortium that builds on CAFS' past history and current momentum.*

Supplemental appendices are available online on the CAFS IUCRC Program Summary webpage:

https://crsf.umaine.edu/forest-research/cafs/program-summary/

Appendix 1: IAB Members
Appendix 2: Student Participants
Appendix 3: Publications
Appendix 4: CAFS Research Projects

Center for Advanced Forestry Systems

CAFS will graduate as a NSF IUCRC in 2025.

1865 THE UNIVERSITY OF MAINE

The University of Maine served as the lead site for CAFS Phase III under the direction of Dr. Aaron Weiskittel, NSF Award # 1915078. Phase III materials, including members, annual reports, and IAB meeting pages, are available via the CAFS webpage:

crsf.umaine.edu/forest-research/cafs