A. Project Overview

Center Need & Technical Focus: The Center for Advanced Forestry Systems (CAFS) was established in 2007 to address challenges facing the wood products industry, landowners, and managers of the nation's forestland. CAFS was originally formed by the North Carolina State University (NCSU), Oregon State University (OSU), Purdue University (PU), and Virginia Tech (VT). Since then, CAFS expanded to nine distinct university sites that currently include Auburn University (AU), University of Georgia (UGA), University of Idaho (UI), University of Maine (UM), and University of Washington (UW). UM has been part of CAFS since 2009 and has benefited from both Phase I (2009-2013) and Phase II (2014-2019) investments from the National Science Foundation (NSF). Since 2017, UM has served had the lead site.

The need for CAFS-related research and training has become more urgent as the forest industry remains in transition after the 2008 US housing crisis. In addition, Federal funding of forest-related research has declined from $1.1 billion in 1962 to <$700 million in 2015 [1]. Following the Great Recession, there have been multiple mill closures, land sales, and bankruptcies as well as sharp reductions in harvests and acres planted along with decreased investments in intensive management practices while pressure for forest conservation have become greater. Additional pressures include the reduction in demand for wood pulp, evolving product markets, lack of skilled labor, the spread of invasive pests, land use/ownership changes, increased wildfires, and greater variability in weather patterns. Despite these challenges, several opportunities exist for the forest industry. These include emerging products (e.g. nanofibers, cross-laminated timbers), new markets for nontraditional forest products (e.g., carbon, water), and growing global demand for wood fiber. Coupled with these opportunities, advances in key technologies and improved forest management techniques offer substantial promise in allowing the forest industry to overcome current challenges. For example, increases in productivity and shortened rotations have occurred in the southern US where pine productivity has increased from 2 to 20 m^3 ha^{-1} $year^{-1}$ in the last three decades alone [2].

This order-of-magnitude increase in productivity is due to the implementation of several management practices including fire control, soil preparation, improved genetics, fertilization, vegetation control, and density manipulation. To increase these yields further, the forest industry must harness emerging technology and develop precision forest management regimes in which the trees, soil, and other vegetation are actively managed at the necessary resolution to optimize value. Implementation of these regimes requires knowledge concerning how a tree's genetic composition interacts with the environment to affect productivity, stem quality, wood quality, and resistance to insects and diseases. In addition, a site-specific understanding of what factors limit production (temporally and spatially) and how contrasting treatments can be used to address these limitations is required. In many respects, intensive and high precision forest management is much like modern agriculture, but it is still firmly based on forestry's strong ecological and physiological foundations. In addition, unlike the annual production cycle of agriculture, sustainable and high-value forest management requires long-term planning, which creates the need for highly robust decision-support tools and refined technologies for monitoring, modeling, and forecasting current as well as future yields across multiple decades.

Given the diversified ownership of commercially managed forests that vary from high investment, single-species plantations of the Southeast and Pacific Northwest to naturally regenerated, mixed species forest widespread throughout the Inland Northwest and Northeast, forestry research and development has tended to be regional in scope, including several long-term university-industry cooperatives (Table 1). This regionalization is also reflected in the evolution of CAFS over the last decade. A primary objective of CAFS was to unify regional cooperatives under a consistent structure and function. This was achieved in Phase I of CAFS with key partnerships established and potential cross-site synergies identified. In Phase II, CAFS continued regional integration of research projects and completed a second multi-site collaborative fundamental research effort. Phase III will have even greater integration of research efforts and a more nationally-relevant focus. For Phase III, all of the original and current sites will continue with

Table 1. Existing regional industry/university forest research cooperatives unified under CAFS.

Site	CAFS Site	Industry/University Forest Research Coops	Year Established
North Carolina State University (NCSU)	2007	Forest Productivity Coop	1969
Oregon State University (OSU)	2007	Pacific NW Tree Improvement Research Coop	1983
		Vegetation Management Research Coop	1993
		Tree Biosafety & Genomics Research Coop	1994
		Center for Intensive Planted-Forest Silviculture	2009
Purdue University (PU)	2007	Hardwood Tree Improvement & Regeneration Center	1998
Virginia Tech (VT)	2007	Forest Modeling Research Cooperative	1979
		Forest Productivity Coop	2002
University of Georgia (UGA)	2009	Plantation Management Research Coop	1976
		Wood Quality Consortium	2000
University of Maine (UM)	2009	Cooperative Forestry Research Unit	1975
University of Washington (UW)	2009	Stand Management Coop	1969
		Precision Forestry Coop	1999
University of Idaho (UI)	2010	Intermountain Forest Tree Nutrition Coop	1980
		Inland Empire Tree Improvement Coop	1973
Auburn University (AU)	2014	Southern Forest Nursery Management Coop	1972

CAFS, except Auburn University (due to changes in membership) and Virginia Tech (due to changes in leadership). However, Virginia Tech will likely rejoin CAFS in the future after the leadership transition.

Phase III's integration and national focus is timely. Emerging technologies and approaches in forestry like Light Detection and Ranging (LiDAR), unmanned aerial vehicles (UAVs), site potential productivity, and forest health risk assessment have created a common research platform across regions. Aggregation within the industry also necessitates a more nationally integrated research program; the top five land owners/managers now account for nearly 30% of US timberland acreage. Given the large number and diversity of forest landowners, CAFS uses an acreage-based dues structure, which allows for a more effective prioritization of research needs. Given the success of this membership structure in Phases I and II, this acreage-based approach will be continued in Phase III.

Center-wide Impact of Phase I & II Accomplishments: The CAFS Industry Advisory Board (IAB) has taken a leadership role in defining research issues and opportunities during Phases I and II. Phase I focused primarily on optimizing forest management regimes and quantifying long-term influences on yield. Across all sites, a total of 27 research projects were completed, which trained 47 MS and 49 PhD graduate students as well as 13 post-doctorate researchers. Of these research projects, 22% were multi-site and resulted in 378 unique peer-reviewed publications; the vast majority (65%) of these publications were co-authored by a graduate student. The projects were relatively balanced across three of the four research focal areas in Phase I, with less focus on forest health (Table 2). A multi-site collaborative fundamental research effort focused on better understanding of tree nutrient uptake following fertilization and involving three sites, namely PU, UW, and VT, was initiated in Phase I and completed in Phase II. Based on the outcomes of that particular effort and IAB feedback, several Phase II proposals on fertilization were initiated.

As CAFS moved into Phase II, the IAB recommended maintaining the original four research focal areas (genetics, growth & yield modeling, forest health, and forest management), as well as adding a wood quality component when UGA and UW joined CAFS in 2009. This continued consistency in research focal areas resulted in several multi-site and -year field/laboratory trials. In Phase II, 30 research projects were initiated and are either still ongoing or completed (75%), with 20% of them being multi-site. These projects trained 84 MS and 50 PhD graduate students as well as 6 post-doctorate researchers and resulted in 309 unique peer-reviewed publications. In most respects, productivity was comparable (e.g. # of projects) or higher (e.g. # of graduate students) in Phase II than Phase I, but it is important to note that several sites (AU, UGA, UI, UM, UW) still remain in the final year or two of Phase II. In addition, despite more diverse research focal areas in Phase II, CAFS maintained a balance across topics, particularly forest management, genetics, and growth & yield. Like Phase I, Phase II included a multi-site collaborative fundamental research effort focused on better understanding competition processes in contrasting forest types. This collaborative effort involved three sites, namely UM, UW, and VT, and developed new methodologies for representing competition in forest, which will get incorporated into future growth and yield models that are widely used by IAB members. This collaborative project with other Phase II efforts as well as changes in leadership at several sites (i.e., NCSU, OSU, PU, UM, UW) have set the stage for the Phase III research plan (Section C).

Site Impact of Phase I & II Accomplishments: UM accomplished two primary objectives during CAFS Phase I: 1) development of a new forest growth & yield model for industrial forests in the Northeast region and 2) refined understanding about how to optimize commercial thinning prescriptions in spruce-fir stands. During Phase II, the UM CAFS site maintained its momentum in improving decision-support tools and commercial thinning prescriptions in the naturally regenerated Acadian forest of northern New England. Our specific Phase II objectives were to: 1) develop growth and yield predictions for diverse genotypes and silvicultural practices; 2) extend the Acadian Variant of the Forest Vegetation Simulator (FVS-ACD) to managed stands in the Northeast US, and 3) enhance our understanding about individual-tree responses to commercial thinning. These projects involved establishing new field trials to provide growth, stem quality, and wood quality data for model development, parameterization, and validation as well as several new projects developing novel approaches to modeling response to commercial thinning. Based on the high priority placed on these research areas by the IAB, substantial funding continued to be directed towards growth & yield modeling and commercial thinning efforts during Phase II. In addition, we pursued new research opportunities with our IAB to address emerging issues including the increase of endemic invasive tree species (i.e., American beech and red maple), effects of widespread partial harvesting, and preparation for the next spruce budworm outbreak.

Required Research & Expertise: UM's expertise and research efforts in CAFS pertain to improving current growth & yield models and broadening understanding about forest management in naturally-regenerated (not plantations) forests of the northeastern US. UM brings a unique focus related to mixed species, multi-cohort forest structure, and partial harvesting not covered by the other CAFS sites. While our focus is distinctive, our modeling and forest management efforts related to naturally-regenerated, mixed species forests are applicable to the Lake States and Intermountain regions of the US. Throughout Phases I and II, UM's facilities and expertise in the area of remote sensing have dramatically increased. Examples include: (1) Establishment of the Barbara Wheatland Geospatial Analysis Laboratory which supports undergraduate education and graduate student and faculty research while advancing the geospatial skills of forestry professionals, including current IAB members; (2) Key faculty appointments in the field of remote sensing, including Drs. Daniel Hayes, Kasey Legaard, and Parinaz Rahimzadeh-Bajgiran; (3) Several large grants including an NSF-NRT (DGE-1828466) led by Dr. Sandra de Urioste-Stone and PI Weiskittel, who are overseeing an interdisciplinary team of UM faculty in developing a new graduate education model to prepare the next generation of conservation science leaders, indirectly supporting the needs of several IAB organizations; and (4) Establishment of the Maine Geospatial

Table 2. Number of CAFS research projects by phase and research focal area.

Phase	CAFS Research Focal Area					Total
	Forest Health	Forest Mgt	Genetics	G&Y	WQ	
I	2 (0)	8 (2)	9 (2)	8 (2)	-	27 (6)
II	4 (0)	11 (3)	5 (1)	7 (2)	3 (0)	30 (6)
Total	**6 (0)**	**19 (5)**	**14 (3)**	**15 (4)**	**3 (0)**	**57 (12)**

Value in parentheses is the number of multi-site projects. Focal areas are forest health, forest management (Mgt), growth and yield (G&Y), and wood quality (WQ).

Institute as part of the University of Maine System. It is also worth noting that CAFS brings important IAB relationships to the table which leverage ongoing education, research, and outreach activities at UM. Given the growth in expertise and other resources at UM, a greater focus on remote sensing will be an important addition to CAFS efforts in Phase III.

B. Site Structure and Operations within the Overall IUCRC Framework

CAFS has successfully delivered applied and relevant research results in support of sustainable forestry to the IAB for over a decade. Moving into Phase III, the *vision* of CAFS is to support the US forest industry by solving problems with targeted, applied, and collaborative research coordinated across multiple university sites. The recently revised *mission* is to optimize genetic and cultural systems to produce high-quality raw forest materials for new and existing products by coordinating and conducting collaborative applied research that transcends species, regions, and disciplinary boundaries.

As outlined in section C, Phase III research efforts will apply CAFS expertise to build upon past successes in the focal areas of forest health, forest management, genetics, growth & yield modeling, and wood quality as well as remote sensing. In addition, CAFS will leverage the resources of individual sites and maintain an efficient organizational structure to meet 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 stakeholders; (4) Provide a long-term strategic vision for the research needs of our IAB, and (5) Create national networking opportunities for universities and industry.

Available Facilities and Infrastructure: UM is the Land Grant and Sea Grant institution for the State of Maine. In 2014, following extensive strategic planning, UM announced a limited portfolio of signature programs which reflect areas of substantial strength targeted for future financial investment. Forestry and the Environment is among the signature programs. This is logical, given that Maine is the most forested state in the US (89% of land area) with a very large commercial forest that is 93% privately owned. Maine supports a diverse forest industry that employs over 38,000 people, is the leading manufacturing exporter in the state (29%), and has an $8-10 billion annual economic impact on the state.

UM's School of Forest Resources (SFR) includes 27 faculty and approximately 11 technical and support staff. The Center for Research on Sustainable Forests (CRSF) led by PI Weiskittel provides a center of excellence for forest-based research efforts and serves as the home for CAFS at UM. The Cooperative Forestry Research Unit (CFRU) is part of the CRSF within UM. Composed of 35 private and public forestland management organizations representing 8.3 million acres across the state (half of Maine's forest area), CFRU's mission is to conduct applied scientific research that contributes to the sustainable management of Maine's forests for desired products, services, and conditions. The CFRU includes 11 research scientists who conduct research in the areas of 1) silviculture and forest productivity,

Table 3. Outcome metrics for the UM CAFS Sites by Phase.

Metric	Phase I	Phase II
Number of Projects	4	7
Undergraduate students	52	68
REU	1	1
MS/MF students	9	13
PhD students	4	3
Total students	66	85
Post-doctoral researchers	3	3
Number of Publications	97 (70% with graduate or post-doctoral co-author)	62 (88% with graduate or post-doctoral co-author)

2) forest modeling, and 3) wildlife ecology and management. UM's CAFS-funded scientists hold appointments within the School of Forest Resources. They, as well as CAFS-funded undergraduate and graduate students, have full access to the Facilities, Equipment, and Other Resources that are described in this proposal.

Center Leadership: The CAFS *Center Director* has primary responsibility for scientific leadership and oversight of Center operations (Figure 1). The Center Director follows and implements the recommendations of the IAB, solicits Center membership, ensures policy and procedure compliance, and oversees the coordination of research activities among the university sites. As of 2017, Dr. Aaron Weiskittel has taken over as Center Director of CAFS after the ten-year tenure of former CAFS Director Barry Goldfarb of NCSU. Dr. Weiskittel is well-prepared for this role. He has served as the UM Site Director and been integrally involved with CAFS since 2009. Dr. Weiskittel is the JD Irving Chair of Forest Ecosystem Management and Professor of Forest Biometrics and Modeling. He also serves as Director of the Center for Research on Sustainable Forests and is a faculty associate at the Senator George J. Mitchell Center for Sustainability Solutions.

Prior to his arrival at UM in 2008, Dr. Weiskittel worked with industrial Douglas-fir and loblolly pine plantations of the Pacific Northwest and Southeast, respectively, as a researcher with the Weyerhaeuser Company, a primary IAB member. His work covers a broad spectrum of spatial scales ranging from individual conifer needles to large regional landscapes. His primary focus has been on the development of applied quantitative tools for forest managers. Since arriving in Maine, he has focused on developing new growth and yield models for the Northeastern US, evaluating stem taper/volume equations, and exploring the potential influence of climate change on forest productivity. Throughout his career, Dr. Weiskittel has worked closely with the forest industry across the US with direct involvement in several regional research cooperatives (e.g. Swiss Needle Cast Cooperative, Stand Management Cooperative, Northeastern States Research Cooperative). During the last IAB meeting, the Executive Committee endorsed Dr. Weiskittel as the next Center Director for CAFS and expressed confidence in his capability to lead the organization through Phase III. Since taking on the role as CAFS Director, Dr. Weiskittel has drafted a strategic plan and technology roadmap for CAFS, which directly addressed IAB feedback that the Center should broaden its scope of activities and identify three to six priority projects that are national in scale as well as relevant to the IAB.

Site Directors/Co-Principal Investigators assist in scientific leadership and administrative functions at the participating university sites (Figure 2). They help to develop and coordinate inter-university research programs and solicit new membership to the Center. At UM, Drs. Brian Roth (CFRU Program Leader), Christian Kuehne (Post-Doctoral Fellow), and Joshua Puhlick (Post-Doctoral Fellow) as well as Cen Chen (Post-Doctoral Fellow) support CAFS research. Additional faculty from the CFRU, SFR, and CRSF will also participate in CAFS research projects as they develop during Phase III. The

CAFS *Industrial Advisory Board (IAB)* is composed of the representatives of both the private and public sector sponsors. In many cases, these sponsors are also members of regional industry cooperatives, such as CFRU which has had a lengthy affiliation with UM. The CAFS IAB reviews ongoing and completed activities and selects new projects. In addition, the IAB provides input to NSF on the functioning of the Center (Figure 2). The IAB strongly influences the priority given to various research projects. Each site appoints a representative to IAB, which provides direction to CAFS's operation and research activities.

Historically, the CAFS IAB met once each year, an approved deviation from standard IUCRC practice because of the long-term nature of forestry research. CAFS is transitioning to meeting *twice* per year with an in-person meeting in June and a virtual meeting in December. The format of the annual June meeting will remain the same as members will review proposed and ongoing CAFS projects and recommend the allocation of funding. CAFS will continue to encourage projects that involve participation by scientists from at least two university sites. The IAB will continue to provide feedback on the relevance and technical merit of the research to the investigators using the IUCRC LIFE Forms. Subsequent to the June meeting, all members will be asked to vote for their preferences among the proposed projects. All full and associate members will have a number of votes proportionate to their financial contribution to the Center. Although sponsoring organizations can have multiple memberships in CAFS as a result of their affiliation with multiple university sites, no one sponsoring member will be permitted to hold more than 25% of the total number of votes on the IAB. The final decision concerning the allocation of funding will follow a specific set of criteria established by the Director's Board (Center and Site Directors) in consultation with the IAB's Executive Committee. The following criteria will inform funding allocation: (1) IAB voting, (2) equality of funding across sites, (3) budget requirements for each project, (4) ongoing commitments to personnel, and (5) opportunities for the development of future collaborations. The proposed December 2018 IAB meeting will include project updates along with business activities such as modifying bylaws, revising the Center's strategic plan, and reporting current and projected fiscal balances.

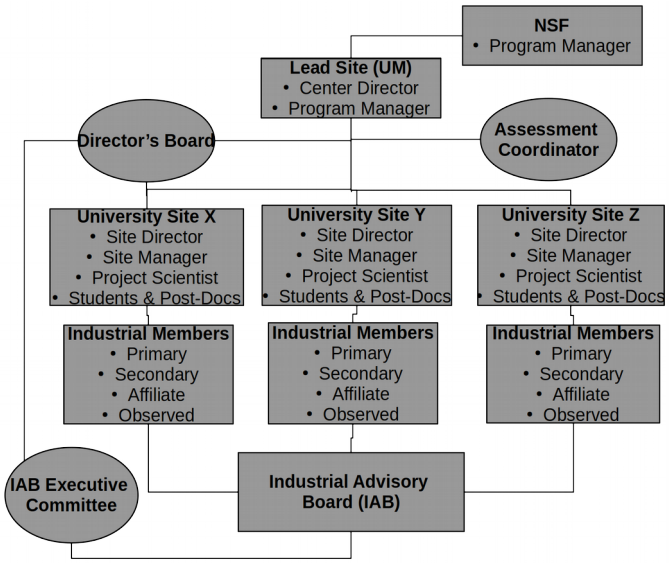

Figure 1. Organization chart for the Center for Advanced Forestry Systems (CAFS). Currently, there are 9 universities and 105 unique member organizations in CAFS representing 19 large corporations (>500 employees), 71 small industry companies, 8 governmental agencies, and 7 non-profit or foundation organizations.

The *Director's Board* consists of the CAFS Center and Site Directors and helps to define the mission, objectives, and guiding principles of CAFS, recruit new members, and review as well as approve the policy documents described in this proposal. The *IAB Executive Committee* is composed of the CAFS Director and officers from the IAB across each site with a nominated Chairperson and Vice Chairperson. This committee works with the Director's Board to advise, assist, and approve all administrative and policy matters affecting the functioning of CAFS. They also help to promote and publicize CAFS accomplishments to legislators, policy makers, and the general public. Currently, Drs. Julio Rojas

(Weyerhaeuser) and John Paul McTague (Rayonier) serve as the IAB Chairperson and Vice Chairperson, respectively. A new IAB Chairperson and Vice Chairperson will be sought in Phase III due to changes in the industry and pending retirements. Finally, the *Assessment Coordinator* (Dr. Stephen McGregor) has been with CAFS since 2015 and annually conducts an independent evaluation of CAFS and provides recommendations. His last report is provided in the supplementary documents and indicates that CAFS remains strong after the completion of Phase II with high interest and support for Phase III.

A *Memorandum of Understanding (MOU)* for CAFS university sites has been developed and formally establishes the relationship between the lead site (UM) and each other site in CAFS. The document is available for review in the supplementary documents section of this proposal and addresses center governance, funding, intellectual property, publication, and confidential policies for CAFS. This MOU has been greatly expanded from previous versions and is being reviewed by the nine university research offices. We fully anticipate that the MOUs will be signed and executed by the start of Phase III. Likewise, a *Membership Agreement* for CAFS (industrial and other non-university) members has been expanded and gives additional attention to intellectual property ownership, publication processes, and liability. The *Center By-Laws* have also been expanded, formalized, and approved in the last year. These by-laws provide an overview of the membership structure, the role of center members, and the specific benefits of membership categories as well as the policies and operations for project proposal solicitation, project selection, and project monitoring. In addition to the CAFS by-laws, each site has a university policy committee, composed of the Site Director and IAB representative. The individual university policy committees focus on member retention, organizational structure, and allocation of funding at their specific site.

Membership Structure and Fees: CAFS has nine sites with a total of 105 unique members representing 19 large corporations (>500 employees), 71 small industry companies, 8 governmental agencies, and 7 non-profit or foundation organizations (Table 3). Membership in CAFS is open to any company, agency, or foundation with an interest in developing advanced technological systems for forest management. Since members own land in various locations throughout the US, several organizations have memberships at multiple sites. For example, two organizations are members at six sites, while one organization is a member at five sites. Consequently, there 152 members in CAFS if non-unique memberships are added.

During Phases I and II, there were *two* categories of membership in the Center. In 2018, CAFS has 50 full or primary members that contribute an annual sum of $25,000 or more and 50 associate members that contribute between $5,000 and $25,000 per year. This two-tiered dues structure allowed us to attract and retain diverse organizations that vary widely in the amount of forestland owned and/or financial resources available to support research. Likewise, membership in CAFS is generally acreage-based with varying rates across sites. This again is related to the diversity of ownership patterns and regional variation in timberland value. For example, current timberland values in the northeastern US are generally $400-700 per acre, while prices in the US Pacific Northwest often exceed $5,000 per acre, which ultimately affects the number of acres any member can own. As mentioned, several of the larger firms in CAFS maintain multiple memberships within- and/or across-university sites and will continue to do so during Phase III. However, in response to NSF concerns and to foster greater clarity as well as equitability among CAFS members, a new membership structure is being proposed for Phase III that directly outlines the benefits and expectations of varying membership levels (Table 4).

The *four* membership categories for Phase III are Primary (annual dues >$25,000), Secondary (annual dues >$10,000), Affiliate (annual dues >$5,000), and Observer (in-kind contributions <$10,000). This membership structure is more consistent with other IUCRCs, addresses the historically varied contributions from members, and clearly articulates the direct benefits of membership. In particular, the membership structure proposed for Phase III streamlines project voting, which has been a challenge in the past. Although IAB voting rights were always proportionate to the members' financial contributions, the weighting structure used was not transparent and could vary year to year. The primary benefits of

membership are voting rights and access to intellectual property. The dues structure was based on past expectations and consistent thresholds across the sites, which are generally acreage-based.

The Director's Board and IAB Advisory Committee will work together during Phase III to develop and disseminate more strategic communications related to CAFS membership benefits to help secure the Center's sustainability. CAFS plans to grow its membership during Phase III as part of its long-term sustainability plan as outlined in the supplementary documents section of this proposal. Phase III will strategically expand the membership beyond the more traditional regional memberships of the past. The national focus in Phase III will likely appeal to national organizations, including but not limited to: National Council of Air & Stream Improvement (NCASI), American Forest Foundation, Sustainable Forestry Initiative (SFI), U.S. Endowment for Forestry & Communities, Inc., and the Climate Action Reserve (CAFS). Previous partnerships with these organizations have existed at CAFS sites in the past.

Intellectual Property: CAFS has not encountered intellectual property issues during Phase I and II, as forestry research tends to be long-term and regional and leverages existing technologies rather than developing new ones. Phase III's national focus and shift to a more technology-driven research agenda could potentially create intellectual property issues. The Center's revised by-laws, membership agreement, and memorandum of understanding more clearly articulate expectations and adopt intellectual property procedures commonly used in other NSF IUCRCs. Only IAB members at the full membership level will have access to intellectual property rights.

Potential Issues Hindering Center & Site: The close collaboration and management among the Center director, site directors, and cooperating researchers has helped to ensure that any on-site or cross-site issues that could put CAFS research at risk are identified and quickly managed. In addition, the CAFS IAB provides annual feedback and recommendations for Center priorities and how key issues affecting the Center are handled. The Center's Assessment Coordinator**,** appointed by NSF, provides an annual review of CAFS activities and helps ensure compliance with guidelines and member satisfaction with the Center's performance. His appraisal supplements the annual reviews of research projects and staff performance conducted by the site directors. Dr. Stephen McGregor currently serves as the CAFS' Assessment Coordinator and he will continue in this role during Phase III. The Center's organizational structure and intentional redundancies help to ensure that all IUCRC policies and operations, including the process for project proposal cultivation, project selection, and project monitoring, are well managed.

For Phase III, potential issues that may hinder CAFS and, in particular, the UM site include: 1) management; 2) sustainability; 3) resources centralization; 4) coordination; and 5) balancing national interests with competing regional needs. Historically, NCSU was the CAFS lead site, and received NSF supplemental funds to manage and coordinate CAFS. UM has taken the lead responsibility and will now rely on internal funding available to the Center for Research on Sustainable Forests as well as the NSF contributions to manage and coordinate CAFS. UM will balance the needs of the Center and site during Phase III; much of this balance has already been achieved given that the transition in leadership between NCSU and UM occurred in Phase II.

Centralization of resources has been a challenge for CAFS in the past and will likely be the primary issue in Phase III. A primary strategy to address this concern is to develop more nationally relevant, multi-site research projects to balance the Center's available resources. In addition, a plan to centralize a small fraction of each site's membership dues will be developed and implemented. Doing this over the next five years of Phase III will help ensure future sustainability and may strengthen the partnership with more forestry and conservation organizations that are national in scope. Industry and non-profit organizations alike recognize the need for a national research organization like CAFS. In addition, a communication strategy and consistent messaging should help with coordination. Finally, balancing national interests with contrasting regional needs will be a potential issue given the regional complexities of the forest industry. In Phase III, the primary objective of CAFS will be to identify and document common research needs across the industry. Based on previous discussions with the IAB and Director's

Table 3. Phase III membership categories with current Phase II members by site.

Membership	AU	NCSU	OSU	PU	UGA	UI	UM	UW	VT	Total
Primary	0	5	4	8	2	8	7	8	8	50
Secondary	16	5	14	0	19	2	8	12	12	88
Affiliate	4	3	0	2	0	0	2	0	3	14
Total	20	13	18	10	21	10	17	20	23	152

Sites are Auburn (AU), North Carolina State University (NCSU), Oregon State University (OSU), Purdue University (PU), University of Georgia (UGA), University of Idaho (UI), University of Maine (UM), University of Washington (UW), and Virginia Tech (VT).

Board, the research areas and projects currently identified in the technology roadmap encompass common issues across regions and more nationally coordinated efforts are needed, which makes them a logical focus for CAFS Phase III. Furthermore, a shift in focus to remote sensing and emerging technologies like LiDAR will allow for national linkages as these are more generalized and less region-specific applications that need attention. In short, CAFS has identified potential risks and developed an effective strategy for mitigating them.

Sustainability Plan: At the conclusion of Phase III, CAFS will "graduate" and no longer be eligible for funding from the NSF IUCRC program. The need for nation-wide collaboration, however, will not diminish and it is imperative that the sites determine how to sustain their research and related broader impacts. Both the IAB and Director's Board have expressed a strong interest in sustaining CAFS, particularly as industry issues become less regional in nature. As stated above and in the Sustainability Plan in the Supplemental Documents, a multi-faceted approach to sustaining CAFS will be refined and employed (Table 5). Private support, including gifts from high net worth private forest landowners, is likely to remain important to individual sites but is not an ideal target for center-wide activity, with the exception of private foundations and corporations with national interests. Consequently, the primary focus will be on centralizing a portion of site resources, seeking new members with more national interests, and Federal grants/contracts. Several potential members have been identified and strategic invitations to future CAFS events will be made. A particularly promising area of potential members are technology companies that derive spatial products. These products are often developed with limited input or data, which may limit their application. By better linking these companies with researchers who could improve the products and the customers who might purchase these products, a strong synergy could be developed and is likely the industry's future direction.

CAFS will pursue Federal grants across a broad array of programs. Logical programs include USDA AFRI's Coordinated Agricultural Projects, which supports large, multi-million dollar projects that often involve multiple institutions with a specified outcome, and NIFA's Integrated Research, Education, and Extension (IREE) Competitive Grants Program that funds integrated, multifunctional agricultural research, education, and extension activities. Within NSF, several potential programs could be explored such as National Socio-Environmental Synthesis Center (SESYNC), Ecosystem Science Cluster, and Accelerating Research through International Network-to-Network Collaborations (AccelNet). An EPSCoR Research Infrastructure Improvement Program Track 2 between UM and UI could also be explored given both are in EPSCoR jurisdictions. Finally, inclusion of a remote sensing research focal area may create funding opportunities with various NASA programs.

C. Research Plan

Overview: In Phase I, CAFS primarily centered on four research areas: genetics; growth & yield modeling; forest health; and forest management. Phase II added a wood quality component to the original

Table 4. Phase III membership types with expected fees and benefits.

Membership Type	Membership Fee	Vote	Intellectual Property Access
Primary	≥$25,000/yr	10 votes per membership	Yes
Secondary	≥$10,000/yr	5 votes per membership	Upon Approval
Affiliate	≥$5,000/yr	0	No
Observer	In-kind (<$10,000)	0	No

four themes. Phase III reorganizes these five topics into three primary focal areas (forest management, forest genetics, and decision-support tools) and adds remote sensing as a fourth focal area. The prior research areas of forest health, wood quality, and growth & yield will be incorporated into the forest management, remote sensing, and decision-support tool themes, respectively. This reorganization reflects national forestry concerns and leverages each site's expertise while creating more cross-site collaborative opportunities (Figure 2).

Specific Research Projects: Three pre-competitive research projects were selected during the last IAB meeting on December 10, 2018 and are vital to the IAB-approved technology roadmap.

UM CAFS PROJECT 1: Assessing & mapping regional variation in site productivity.

Project Objective: Precision forestry is based on the concept of optimizing the best management practices on each acre of ground. One of the primary determinants of optimal management practices is the potential site productivity, which influences the growth and development of forests. However, multiple metrics of potential site productivity are used by the forest industry with an unclear understanding of their primary differences and how they might vary across regions [3]. Consequently, the primary objective of this project will be to develop a consistent and biologically-meaningful metric of potential site productivity that can be related to a variety of environmental factors and mapped across the various regions. Proposed Team: Rachel Cook (NCSU), Mark Coleman (UI), Cristian Montes (UGA), Kim Littke (UW), Doug Jacobs (PU), Aaron Weiskittel (UM). Plans to Address Broadening Participation: This team includes several CAFS institutions and female PIs. Additional collaboration will be sought from other institutions to broaden the study scope and other

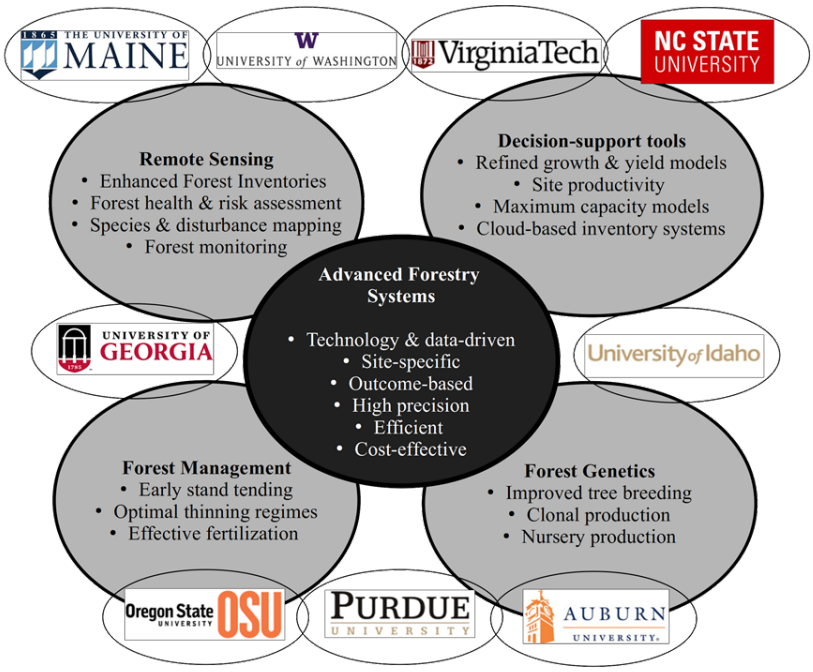

Figure 2. The four research focal areas for CAFS Phase III with site expertise and linkages identified.

Table 5. Specific targets for CAFS sustainability.

Federal Programs	USDA – US Forest Service, AFRI, NIFA; NSF – SESYNC, ESC, AccelNet; NASA – ROSES, CCS, CMS, LCLUC
Private Foundations & NGOs	American Forest Foundation, Sustainable Forestry Initiative, U.S. Endowment for Forestry & Communities, Inc.

expertise. Diverse graduate students will be recruited using strategies outlined in UM's NRT project (PI DeUrioste-Stone with Weiskittel as Co-PI, #182846 NRT: Enhancing conservation science and practice: An Interdisciplinary program). Industrial Relevance & Appropriateness for Center: This will be a national-scale project that will be relevant for all industry members. Potential site productivity is generally assessed using site index or the dominant height at specified age, which is known to have several limitations and is difficult across the landscape due to high measurement error potential and inherent variability. This project will require cross-site collaboration and sharing of data, which makes it a highly logical and necessary center activity. Deliverables: The primary deliverables will be a harmonized dataset for assessing regional variation in site productivity, a developed methodology for quantifying site productivity, high-resolution raster layers of key site-level environmental variables as well as the predicted site productivity metric, and equations for deriving these various attributes. Annual progress reports and presentations will be provided at annual IAB meetings as well as a final report and presentation. At least three peer-review publications and conference presentations will be expected from this project. Project Duration, Milestones, & Annual Proposed Deliverables: *Year 1* milestones and deliverables will be the identified data required for the project, outlined plans for data compilation, and preliminary derivation of several site productivity metrics. *Year 2* milestones and deliverables will include the finalized data for site productivity modeling, a comparison of alternative site productivity metrics, key rasters for soils, climate, and topography, and a preliminary model for relating the site productivity metric to the environmental factors. *Year 3* milestones and deliverables will be the final model for relating the site productivity metric to the environmental factors, high-resolution maps of the predicted site productivity metric, and evaluation of the developed metric's performance in comparison to the more traditional site index. Industry Need: Metrics of site productivity, particularly site index, are widely used by the forest industry for a variety of purposes including land acquisition/disposition, investments in forest management activities, and projection of future conditions. Although site index has a long history and is widely used, it is known to have multiple limitations. More recently developed site productivity metrics like biomass growth index and maximum yield show more consistent behavior as well as improved relationships with additional site factors like soils and climate. The ability to better map site productivity across the landscape will reduce the need for costly measurements for site productivity assessment and an improved ability to better match management actions with site conditions. This improves the likely return on investment for any management actions taken. Available Research Facilities: Sites have various datasets for conducting this project, which include long-term measurements of stand conditions, high-resolution rasters of environmental factors, and the computational ability to process as well as produce complex models of site productivity. These resources will be combined to produce nationally-consistent maps of site productivity and the most influential site factors. Time to Completion: 3 years. Cost: Funding for one doctoral-level graduate research assistant (0.5 FTE) for approximately $25,000 across three years or a total of $75,000.

UM CAFS PROJECT 2: Assessing & mapping regional variation in site carrying capacity

Project Objective: Maximum site carrying capacity determines the number of individuals of a certain size per unit of area that an defined stand can support and maintain. The attribute is a complex function of species composition, genetics, environmental conditions, and stand structure. Prior research has indicated that maximum site carrying capacity is primarily determined by stand purity (% dominance by primary

species), stand origin (natural vs. planted), site index, and skewness of the diameter distribution. The primary objective of the research project is to synthesize a range of regional datasets to test the general robustness of these prior findings [4] and develop derived maps of predicted maximum site carrying capacity that can be provided to industry members. Proposed Team: Eric Turnblom (UW), Doug Maguire (OSU), Cristian Montes (UGA), and Aaron Weiskittel (UM). Plans to Address Broadening Participation: Team currently includes several CAFS institutions from different regions. Additional collaboration will be sought from other institutions as well as specific industrial members to broaden study scope and other expertise. Recruitment of diverse graduate students will be pursued using strategies outlined in UM's NRT project and linkages to that effort evaluated. Industrial Relevance & Appropriateness for Center: This will be national-scale project that will be relevant for all industry members. Maximum site carrying capacity determines stand productivity, is necessary for optimizing planting or residual thinning schedules, refining growth and yield projections, and maintaining compatible species compositions in naturally-regenerated stands. This project will require cross-site collaboration and sharing of data, which makes it a highly logical and necessary center activity. Deliverables: The primary deliverables will include 1) a harmonized dataset that estimates the maximum stand density index (SDImax) for a range of study locations throughout US commercial forestlands; 2) an equation that relates the observed site-specific SDImax to various species functional traits, stand attributes (e.g., structure, diameter distribution, site index), and environmental factors (e.g., soils, topography, climate); 3) and a high-resolution (10-30 m) raster map of predicted SDImax based on the factors identified in the developed equation. Annual progress reports and presentations will be provided at annual IAB meetings as well as a final report and presentation. At least three peer-review publications and conference presentations will be expected from this project. Project Milestones & Annual Proposed Deliverables: *Year 1* milestones and proposed deliverables will be the identified regional datasets and the final harmonized dataset to be used for analysis. *Year 2* milestones and proposed deliverables will be the harmonized dataset linked to the various environmental factors. *Year 3* milestones and proposed deliverables will include the finalized model for predicting SDImax from environmental factors and high-resolution maps of SDImax across the various regions being examined. Industry Need: Determination of optimal planting or thinning residual densities are an important management decision that influences stand development and final value. Currently, most regions use a single value of SDImax for each species that guide stand density management decisions and growth and yield projections. However, there is growing evidence that SDImax is highly dynamic and variable across the landscape, which can make optimizing management decision or growth projections difficult. An improved understanding of SDImax variation and the ability to predict it at rather high spatial resolutions will help refine future stand management. In addition, this will allow for the use of a nationally-consistent variable for defining management, while currently a wide variety of variables are used. Available Research Facilities: Similar to CAFS Project #1 (outlined above), all sites have relevant datasets that can be contributed, which include long-term measurements of stand conditions, high-resolution rasters of environmental factors, and the computational ability to process as well as produce complex models of site maximum carrying capacity. These datasets will be combined in this project to produce nationally-consistent maps of maximum carrying capacity and the most influential factors. Time to Completion: 3 years. Cost: Funding for one doctoral-level graduate research assistant (0.5 FTE) for approximately $25,000 across three years or a total of $75,000.

CAFS PROJECT 3: Mapping species composition & past disturbance using optical sensors

Project Objective: Forest inventory assessments are often conducted using ground-based methods that significantly limit their spatial and temporal resolution, which can make precision planning efforts a challenge. Optical sensors like LandSat and Sentinel-2 offer the ability to provide more routine and spatially complete assessments. However, using remote sensing data for forestry has often been challenged by canopy complexity, cloud/snow cover, and partial disturbances. In recent years, multi-

objective machine learning algorithms have been developed and deployed for specific applications, particularly species and partial disturbance mapping [5]. These algorithms have primarily been applied in the extensively managed, mixed-species forest in the Northeast, but might have value for other forest regions. In addition, the Sentinel-2-II A and B satellites, which were launched in 2015 and 2017, respectively, offer much higher temporal (6-12 days) and spatial resolution (10-20 m) when compared to LandSat, which creates potentially new opportunities for forestry applications like change detection. Proposed Team: Kasey Legaard (UM), Aaron Weiskittel (UM), Paul Gessler (UI), Jeff Hepinstall-Cymerman (UGA). Plans to Address Broadening Participation: Project team currently includes three CAFS institutions. Additional collaboration will be sought from other institutions to broaden study scope and other expertise. Industrial Relevance & Appropriateness for Center: Forest inventory data is the primary information used in most business planning decisions for the forestry industry. Ground-based inventories are expensive to maintain and implement, while having both limited spatial and temporal resolution. There is a strong need for more real-time, spatially-explicit, and high-resolution data for key decision-making processes. Beyond species composition and forest disturbance, there are several other potential remote sensing applications for forestry. These include forest health, wildlife habitat, and biomass/carbon mapping, all of which are even more difficult and expensive than traditional forest inventory assessments, which focus primarily on timber value. This is a logical project for the Center as the industry members own various tracts of forests throughout North America and maintain ground-based inventories, which would allow for evaluation of the derived maps across a very wide range of conditions. Deliverables: The primary deliverables from this project will be maps of key forest attributes across a range of conditions and verification of the algorithm's robustness as well as accuracy. A final report and presentation will be provided at the annual IAB meeting. Project Milestones & Annual Proposed Deliverables: Key project milestones will be: (1) identification of the specific geographic area of interests across sites and member ownerships; (2) compilation of the necessary ground-data needed for map development and evaluation; (3) production of the maps for each area of interest and shared with appropriate site/industry partner; (4) potential refinement of the maps based on formal evaluation, and (5) complete analysis documenting overall accuracy across the study areas. Industry Need: The use of remote sensing has been relatively limited in forestry due to the complexity of issues faced. Moderate resolution satellites like LandSat have shown promise, but often show key biases and have limited temporal (~2-3 weeks) and spatial resolution (~30 m). Newer satellites like Sentinnel-2 provide new opportunity with additional bands as well as higher temporal and spatial resolution. Limited application of Sentinnel-II B data in forestry has been provided due its recent launch in 2017. Given the increasing information needs of the forest industry and forest certification expectations, more timely and accurate geospatial data is needed. Landowners have commonly identified limited geospatial resolution as a primary business barrier. This project has the potential to demonstrate the capacity of remote sensing and powerful machine learning algorithms to produce reliable and highly accurate geospatial information. Available Research Facilities: The University of Maine has developed a software framework for downloading, processing, and calibrating multi-objective machine learning algorithms to produce high-resolution maps from remote sensing imagery. Additional research needs include defined geographic areas of interests and any available ground-based data in or around those identified areas Time to Completion: 1 year. Cost: Partial funding for one faculty research associate (Legaard) and one undergraduate student technician for a total project cost of $50,000.

D. Results from Prior NSF Support: Award Number: IIP-0855370; PIs: Robert G. Wagner (PI), Aaron Weiskittel (Co-PI); Amount: $350,000; Period of Support: 1/15/2009 to 2/14/2014; Project Title: University of Maine Proposal for Joining the NSF Center For Advanced Forestry Systems; Accomplishments: See Impact of Phase I Accomplishments section above; Intellectual Merit: University-based, industry-supported, cooperative research programs have been extraordinarily successful at achieving research and technological advances on topics of great relevance to forest industry. However,

the ability of these programs to focus on specific disciplinary topics (in response to industrial guidance) has also been a limitation. Many of the problems and opportunities facing the management of forests today bridge disciplinary and regional boundaries. CAFS has been extraordinarily successful at providing the administrative and funding structure needed for national, interdisciplinary, scientific collaboration among researchers in these coops to make significant progress in increasing forest productivity through forest genetics, site manipulation, and better growth & yield modeling. Broader Impacts: Research conducted by CAFS increased the competitiveness of forest products industries and forest landowners by solving problems at multiple temporal and spatial scales, and by determining fundamental solutions that transcend traditional tree species, regional, and disciplinary boundaries. Industrial members benefited by becoming knowledgeable about a wider range of technological capabilities. In addition, technology transfer between CAFS scientists and member personnel fostered rapid implementation of new technologies. Graduate student training was featured in CAFS research and technology transfer. Opportunities will continue to be sought to involve undergraduate students in CAFS research activities, exposing them to the excitement of forest science and encouraging them to pursue graduate education. Publications: Key publications were [5-10]. Evidence of Research Products and Their Availability: See Impact of Phase I and II Accomplishments section above, and other Supplementary Documents section of this proposal. Award Number: DEB-1313688; PIs: Erin Simons-Legaard (PI), Kasey Legaard (Co-PI), Jessica Leahy (Co-PI), Aaron Weiskittel (Co-PI); Amount: $248,742; Period of Support: 6/1/13-5/31/15; Project Title: CNH-Ex: An Analysis of Disturbance Interactions and Ecosystem Resilience in the Northern Forest of New England; Accomplishments: The focus of the project is to couple human- and ecologically-driven models to answer important questions about natural resources management. Preliminary work on the project has started and the results indicate that the models can be coupled, which will allow exploration of some key research questions. Intellectual Merit: This project worked to understand the interactions between natural disturbances, human decisions on land use, and key ecosystem properties. This involved linking agent-based models of human behavior with a large landscape ecosystem model, which was used to allow explore multiple novel research questions about humans and how they interact with the natural environment. Broader Impacts: The broader impact of this project answered basic questions on (1) the sensitivity of landowner decisions to market conditions and the actions of their neighbors; (2) the role that natural disturbances plays in influencing landowner actions; and (3) how changes in land use will influence forest ecosystem services such as carbon sequestration and wildlife habitat potential. Addressing these novel and critical questions not only advanced the science of integrated complex systems, but helped to guide broader forest policy and landowner decision making. Publications: Key publications were [11, 12]. Evidence of Research Products and Their Availability: Key research products were an extension to the LANDIS-II model described in [12] and spatial maps made available. Award Number: DGE-1828466; PIs: Sandra De Urioste-Stone (PI), Aaron Weiskittel (Co-PI); Amount: $2,998,314; Period of Support: 9/1/18-8/31/24; Project Title: Enhancing conservation science and practice: An Interdisciplinary program; Accomplishments: An interdisciplinary curriculum will be created based on active learning models, problem-based internships, and collaborative research that integrates biophysical and social sciences. The MS and PhD concentration in integrated conservation systems targets the challenge of managing natural resources under changing socio-ecological conditions. Intellectual Merit: Train students through an innovative transdisciplinary program based on collaborative, solutions-driven education, professional development, and engaged research models that integrate biophysical and socioeconomic sciences. Our goal is to build a well-trained and broadly-experienced workforce to advance conservation solutions that would ultimately lead to enhanced resilience of socio-ecological systems. Broader Impacts: The overall trainee program approaches will be scalable to other US Land and Sea Grant universities and other centers of higher education abroad offering graduate programming committed to coupling human and ecological systems Publications: No publications have been produced from this project yet. Evidence of Research Products

and Their Availability: No research products have been produced from this project yet given its recent start in September 2018.

E. Broader Impacts: Research conducted by the Center for Advanced Forestry Systems (CAFS) during Phase III will continue to *enhance the competitiveness of the US forest products industries* by solving problems at multiple temporal and spatial scales, and by determining fundamental solutions that transcend traditional tree species, regional, and disciplinary boundaries. This is a vital transitional period for the forest product industry that is just starting to recover from the Great Recession, and faces increased demand for lumber and emerging products like cross-laminated timbers. Industrial and non-profit partners with an interest in the nation's forests will benefit by becoming knowledgeable about a wider range of technological capabilities to sustain healthy forests, particularly with the increased focus on key decision-support tools and remote sensing research areas for CAFS Phase III. In addition, technology transfer between CAFS scientists and industry personnel will lead to the more rapid and efficient implementation of several new technologies in forestry such as unmanned aerial vehicles (UAVs) and Light Detection and Ranging (LiDAR), which are rapidly changing how forests are measured, monitored, and managed. Graduate student training will continue to be featured in CAFS research and technology transfer. These students will be unique in the forestry sciences because of their applied problem-solving skills using interdisciplinary techniques across multiple scales. Aggressive recruiting for graduate students among under-represented groups will continue to be conducted, increasing the diversity of the workforce for both academia and industry. Undergraduate students, including women and many who are among the first generation in their families to attend a college or a university, will remain engaged in CAFS research activities and benefit from exposure to the excitement of forest science and the potential of graduate education and STEM careers. The broader scientific community will benefit from refereed publications and presentations at scientific meetings. The nation as a whole will benefit from healthy forests that are vital to the world's ecological, social, and economic health. Forests provide a major part of the Earth's oxygen and remove and store a substantial amount of atmospheric CO2., while serving as habitat for much of the world's plants, animals, and microorganisms—and recreational and spiritual opportunities for its people. Today, forests provide the wood that continues to be the major source of fuel for cooking and heating throughout much of the world. Wood is also a *major economic commodity*, serving as the raw material for building materials, furniture, paper, packaging, and now as a feedstock for bioenergy, biofuels, and biomaterials. The direct impact of forestry on the national economy is significant. To illustrate this, more than *2.7 million jobs depend on forests*, representing a payroll of over $110 billion. Forestry has a *$100 billion economic impact* or >5% of the US's manufacturing GDP.

F. Intellectual Merit: Over the past 50 years, key forest science research has taken place in university-based, industry-supported, cooperative research programs, which continue to be extraordinarily successful at achieving research and technological advances on topics of great relevance to the forest industry. However, the historic focus on specific disciplinary and regional topics (in response to industrial guidance) has become a limiting factor. Many of the problems and opportunities in managing forests today bridge disciplinary and especially regional boundaries. To achieve the technological advances needed for 21st century challenges, existing university/industry cooperatives must approach research questions at multiple spatial and temporal scales, including the molecular, cellular, individual-tree, stand, and ecosystem levels. CAFS has been extraordinarily successful over the past 11 years at providing the administrative and funding structure needed for national, interdisciplinary, scientific collaboration among researchers in these cooperative research programs to make significant progress in the areas of remote sensing, site-specific management prescriptions, and decision-support modeling. The next generation of valuable new knowledge is expected to continue to increase and become fully sustainable through initiatives planned for Phase III of CAFS. This is particularly timely and relevant given the current transitions happening in forest industry.