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silviculture

Adaptive Silviculture for Climate Change: A National Experiment in Manager-Scientist Partnerships to Apply an Adaptation Framework

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Forest managers in the United States must respond to the need for climate-adaptive strategies in the face of observed and projected climatic changes. However, there is a lack of on-the-ground forest adaptation research to indicate what adaptation measures or tactics might be effective in preparing forest ecosystems to deal with climate change. Natural resource managers in many areas are also challenged by scant locally or regionally relevant information on climate projections and potential impacts. The Adaptive Silviculture for Climate Change (ASCC) project was designed to respond to these barriers to operationalizing climate adaptation strategies by providing a multiregion network of replicated operational-scale research sites testing ecosystem-specific climate change adaptation treatments across a gradient of adaptive approaches, and introducing conceptual tools and processes to integrate climate change considerations into management and silvicultural decisionmaking. Here we present the framework of the ASCC project, highlight the implementation process at two of the study sites, and discuss the contributions of this collaborative science-management partnership.

Keywords: adaptation, adaptive management, climate change, partnerships, silviculture

Today's natural resource managers face a mounting set of challenges requiring more knowledge, skill, and creativity than ever before. Complex socio-ecological challenges stemming from climate change and associated stressors (i.e., drought, insects, disease, and wildfire), changing policy direction within agencies, and a paucity of resources and funding, result in a suite of challenges to designing and implementing adaptation strategies in the face of climate change. The US Department of Agriculture (USDA) and Department of

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the Interior have mandated public agencies to plan for and manage the anticipated impacts of climate change. Natural resource professionals may have a desire to address climate change with their management; however, numerous barriers to doing so have been identified, including inadequate information at spatial and temporal scales relevant and accessible to managers, shifting management priorities, and a lack of time, funding, and training for managers to learn how to integrate climate change considerations into operational management (Kemp et al. 2015).

We have responded to these varied and complex needs by designing the Adaptive Silviculture for Climate Change (ASCC) project, a long-term research network that addresses barriers to implementing climate-informed management strategies. The core of ASCC is the manager-scientist partnership that generates robust, operational examples of a range of options for integrating climate change adaptation into silvicultural planning and on-the-ground actions designed to facilitate adaptive responses to uncertain future climate conditions and associated stressors. The ASCC project draws heavily on tools created through a management-focused effort called the Climate Change Response Framework[1] (Janowiak et al. 2014) but couples the management tools with a rigorous scientific design. Specifically, ASCC does the following: it provides training opportunities for natural resource managers to learn about climate change impacts and vulnerabilities relevant to local management goals, while acquiring tools for developing appropriate adaptation approaches and tactics; and it develops a multiregion, statistically rigorous study with ecosystem-specific climate change adaptation treatments using manager-scientist partnerships at the local and national levels. Although this study is driven by climate change concerns and uncertainty, the framework we describe herein is broadly applicable to diverse emerging natural resource issues associated with uncertainty in future forest conditions and dynamics. The primary goals of this article are to describe the climate change framework that was used, driven by a manager-scientist partnership, to apply forest adaptation concepts to a variety of forest ecosystem types in a multiregion study. Moreover, we articulate a set of testable research questions around our current understanding of adaptation options to test what approaches and associated silvicultural sys-

Sidebar 1. Adaptive Silviculture for Climate Change: A Manager Perspective

With an uncertain climate future, land managers are facing uncharted forest dynamics, and the science to support decisionmaking is evolving. We need to be nimble, to manage our forests alongside the science as it develops, and be courageous in trying innovative and collaborative practices. The ASCC project has taken that approach to help us use the best available science while also contributing to research that will further inform our future decisionmaking. The Minnesota ASCC site on the Chippewa National Forest is located in our red pine ecosystem, which is important both ecologically and economically in this state. For more than a decade we have been working to restore long-lived conifers to the northern Minnesota landscape, yet have many young stands of red and white pine that will grow into an uncertain climate future. Through this study, managers will gain insight into strategies to manage future stands as well as those that we currently have on the landscape.

Learning has been a key thread throughout the development and implementation of this project. This project began by establishing a common understanding of the potential climate change effects and broad strategies for dealing with these effects (resistance, resilience, and transition). Some of these concepts fit our current management regime, while others caused us to stretch our imagination to new ways of doing business. As we began planning and implementing the treatments, our scientist partners were open to many of the treatment ideas and management constraints our managers brought forth. For example, writing clear prescriptions to meet the ASCC scientific objectives with terms that are also reportable in our databases was a challenge at first, but we worked together to make the prescription terminology compatible across research specifications and Forest Service databases. Timber sale administration, seedling orders, and timber sale receipts, while procedures in which our managers have expertise, all introduced complexities that required collaboration and communication with the scientists to meet management objectives and maintain the integrity of the study. Approaching this project with an attitude of learning and open communication has led to early successes and built the foundation for future work as we learn how best to prepare our forests for climate change.

When we delve into the details of potential climate change effects, it is easy to become overwhelmed by the uncertainty and the high potential for loss and change. I prefer instead to look for the opportunities to continue managing forests to be diverse, resilient, and valuable to all of us. I believe the work we are conducting in this manager-scientist partnership is critical to our understanding of how we'll manage forests in the face of climate change. The ASCC project demonstrates how land managers can be innovative and adaptive, driving new alternatives for natural resource management.

Management and Policy Implications

The shortage of scientifically robust, replicated, operational-scale research on forest adaptation to climate change has left forest and natural resource managers with little information on and few examples of on-the-ground adaptation approaches that could work for their forest ecosystems. The Adaptive Silviculture for Climate Change (ASCC) project is establishing a national network of long-term silvicultural research sites across multiple regions and a diversity of forest types to test a range of adaptation approaches and to provide managers with the tangible demonstrations needed to inform climate-adaptive decisionmaking in their forest management. Furthermore, the ASCC project provides managers and scientists with training on integrating climate change considerations into planning processes and identifying locally appropriate adaptation approaches and tactics. The main goals of the ASCC project ultimately serve to advance understanding within the forest management community of how management can foster adaptive responses to the impacts of uncertain climate futures. The science-management partnerships built through this project help inform the relevance of the research, as well as advance communication on climate change adaptation at a national scale.

tems best meet management goals. Finally, we illustrate how we applied these concepts as part of a new era of long-term silvicultural studies with two examples where this process has been implemented. We conclude with a discussion of lessons learned as well as directions forward.

Process/Framework

Regional ecosystem vulnerability assessments and related climate change planning workshops (e.g., Swanston et al. 2011, Swanston and Janowiak 2012), in addition to climate change training delivered as part of the National Advanced Silviculture Program (Nagel et al. 2010), have fostered a growing recognition that the forest research and management communities lack an ability to assess the efficacy of adaptation strategies and that field examples demonstrating different adaptation approaches are needed. To this end, we organized a "science team" of experts in climate change, forest management research, and statistics to refine a framework for application to a long-term, experimental silviculture study that could be implemented at multiple, ecologically distinct locations.

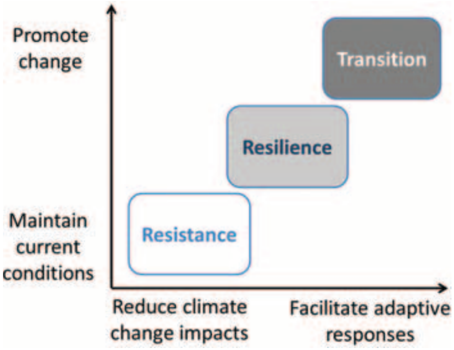

Figure 1. Adaptation options used in the ASCC study, representing a continuum of management goals related to levels of desired (or tolerated) change in ecosystem attributes (represented here on the vertical gradient) and mechanisms for coping with climate change (here, the horizontal gradient).

The study is designed to develop and test silvicultural systems along an adaptation gradient including no action, resistance, resilience, and transition (Figure 1; Table 1) using definitions modified from Millar et al. (2007). By designing, implementing, and monitoring a spectrum of treatments across this adaptation gradient, managers and scientists will be able to learn how well various adaptation options accommodate a range of potential future climate change conditions, at an operational spatial scale, and across a variety of ecosystem types and geographic regions. The design of site-specific treatments and study implementation elements is determined in an initial ASCC workshop at each study site, which serves as the kickoff to the site's involvement in the national project.

The "adaptive" nature of the ASCC project includes not only the design of adaptation actions and associated metrics but also adaptation of management over time to maintain the treatment stands within the silvicultural system designed for each treatment. Additional effort and investment would probably be required to maintain the species composition and structure of stands under the silvicultural system designed for each *resistance* treatment. The more flexible composition and structural goals of the silvicultural systems designed for the *resilience* treatments are hypothesized to enable stands to rebound from disturbances and tolerate a wider range of climate shifts. Fundamental and in some cases novel alterations to species composition and structure exemplify the silvicultural systems designed for each *transition* treatment with related planning for alternate and adaptive actions over time. Both stand response and ongoing management needs will be factors in how we assess the efficacy of each treatment.

Basic Parameters and Questions of the ASCC Study

The intention of the study is to create a network of installations across the United States using a common experimental design that is fully replicated within each site, allowing for both intra- and intersite comparisons of various adaptive management approaches. We developed a set of site-level minimum standards that need to be met for a site to be considered part of the national network (Figure 2). These include replication, a minimum treatment size of 25 ac, and adherence to a core measurement protocol within a determined evaluation window (short- and long-term). Because we are designing a long-term study, the most interesting measurable results will come decades into the future; therefore, some of the core minimum data collected immediately pre- and posttreatment (Table 2) will be used to parameterize vegetation models (e.g., the Forest Vegetation Simulator) (Crookston and Dixon 2005) to facilitate testing treatment responses in the near term.

Conceptually, we are testing these management-related ideas: (1) Will adaptation approaches and treatments work in a real-world context to meet local management goals and objectives? (2) Are the treatments silviculturally feasible (and also fiscally and socially) and will they work within the requirements of a given forest plan? (3) How does our idea of desired future conditions (DFCs) change with each treatment type, and is this important silviculturally? (4) What does it mean to deliberately create a future-adapted ecosystem, and why would a manager choose to do this? And, (5) What

Table 1. Broad treatment definitions and goals of the ASCC project.

Treatment	Experimental treatment definition	Experimental treatment goal
Resistance	Actions that improve the defenses of the forest against anticipated change or directly defend the forest against disturbance to maintain relatively unchanged conditions.	Maintain relatively unchanged conditions over time.
Resilience	Actions that accommodate some degree of change, but encourage a return to a prior condition or desired reference conditions after disturbance.	Allow some change in current conditions, but encourage an eventual return to reference conditions.
Transition	Actions that intentionally accommodate change and enable ecosystems to adaptively respond to changing and new conditions.	Actively facilitate change to encourage adaptive responses.
No action	Since climate change impacts all forest globally, we cannot maintain a true "control." With this in mind, we consider an approach in which forests are allowed to respond to climate change in the absence of direct silvicultural intervention as an appropriate baseline for many questions.	Allow forests to respond to climate change without direct management intervention.

Modified from Millar et al. 2007.

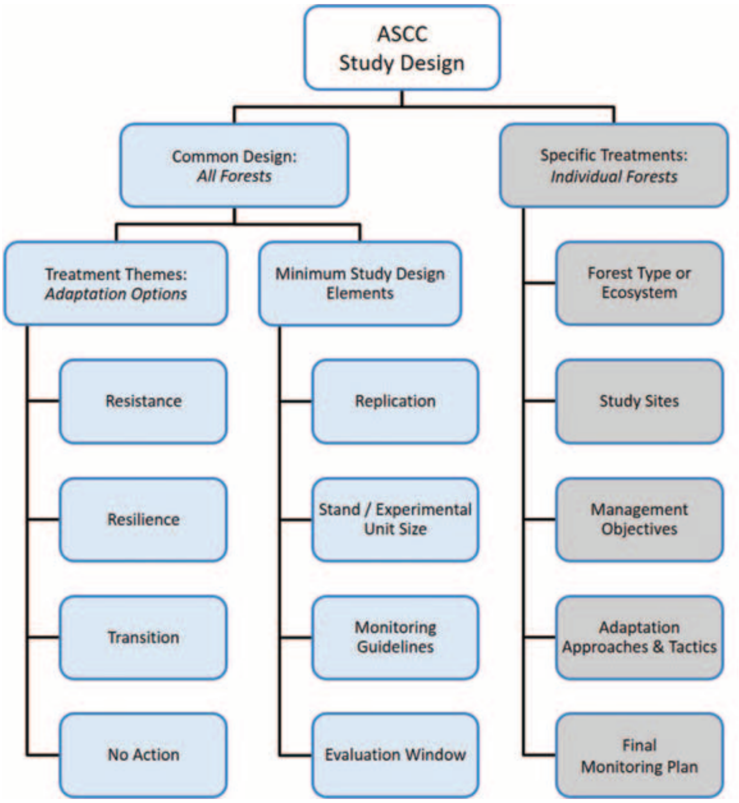

Figure 2. Whereas some elements of the ASCC research design are common to all participating forests (left and middle), aspects that are unique to each forest (right) are designed with input from local managers and experts.

Table 2. Key response variables to be collected at each ASCC site.

Sample	Species composition	Forest health	Productivity
Overstory	Species richness Species diversity Relative density Relative dominance	Mortality Crown density Crown dieback Live crown ratio Tree damage (Damage Severity Index)	Biomass increment Basal area increment
Midstory	Species richness Species diversity Relative density Relative biomass	Relative density or biomass of invasive species	Biomass increment
Ground layer	Species richness Species diversity Percent cover by species	Percent cover of invasive species	Biomass increment

tradeoffs exist between achievement of adaptation objectives and other common objectives for a given region and ecosystem type?

The scientific questions to be addressed through hypothesis-driven research include the following: (1) Is there a significant effect of the treatments on forest conditions and processes over time, and do they differ significantly from each other at each site? (2) How do hypothesized treatment responses (DFCs) compare with actual responses observed in the future? (3) Do these treatments achieve what they were designed for; i.e., do they meet the stated management goals at 5 or 10 years, and will criteria emerge to enable managers to identify which treatments perform best? And (4) Are there trends in which treatment (resistance, resilience, transition, or no action) performs better than other treatments at meeting DFCs and adaptation goals across all ASCC sites?

The ASCC project is designed to work with resource management realities and national forest decision frameworks while generating critically needed research. The study process allows deliberate on-the-ground and statistical testing of broad, high-level conceptual adaptation options appropriate to the management of public lands (Millar et al. 2007, Joyce et al. 2009). The design of the study (size and replication of treatments) also lends itself to the overlaying of additional multidisciplinary research questions and hypotheses specific to each ecosystem type. Emergent criteria for evaluating the performance of each of the treatments (and the site-specific silvicultural systems designed to achieve them) will be developed for the study across sites to address the overarching research questions. More detailed criteria specific to each site will further be defined to identify thresholds for future actions that are part of each silvicultural system and to address the specific research questions and hypotheses pertinent to each site. As the ASCC is a network of research sites with a consistent study design implemented across distinct ecosystem types, scientists and managers will be able to leverage a shared framework to further reveal trends and measure the efficacy of adaptive management approaches across the network, adding to the level of inference and knowledge gained from the study.

Site Selection

Establishing partnerships is key to the success of this project. First, a "site lead" scientist with a silvicultural background is crucial to working effectively with the national project investigators and bridging with local management staff to coordinate all research and implementation efforts and to ensure that the site follows the national framework and protocol. Additional key scientists in related disciplinary areas may also be identified as part of a core science team at each site. Management staff that enable the successful design and implementation of the study include forest managers, timber sale administrators, climate change coordinators (if applicable), policy and planning staff, fire officers, and wildlife, water, and cultural resources staff. In addition, leadership engagement (for USDA Forest Service sites, this includes District Rangers and Forest Supervisors) provides direction and ensures follow-through. Commitment to long-term, large-scale silviculture research and a desire to develop and test adaptation approaches are also essential attributes that must be shared among the managers and scientists involved with the study.

In the ASCC project development, the site lead scientists and study sites have generally been selected in tandem. The study forest should be contained on a site (e.g., national forest, experimental forest, or university forest) deemed to be potentially vulnerable to climate change, have high societal value (timber, recreation, water, biodiversity conservation, or other.), and have a high institutional commitment to successful implementation of the treatments. We also looked for climate change-related information that already exists, such as ecosystem vulnerability assessments, to help guide site selection, inform the overall process used, and identify potential experts who might contribute to the workshop and research implementation. Building on and furthering existing information is a core strength of this approach.

Workshop and Experimental Design Process

Before development of each workshop, the project principal investigators (PIs), site lead scientists, one to two key management staff, and one to two other core scientists met (in person or remotely) to begin summarizing existing information, to identify stakeholders and constituencies for various elements of the workshop, and to identify speakers and members of an "expert panel" who participate in designing the experiment. Site-level information including inventory data, relevant forest plan parameters, and fine- and broad-scale contextual information for the study was compiled, and any information and resource needs were identified. Invitations were sent to the various audiences with the workshop broken down into two parts.

The first day of each workshop served as a stand-alone training for natural resource professionals following the approach outlined by Janowiak et al. (2014). These training sessions began with presentations covering climate science basics, climate trends, and a synthesis of impacts and vulnerabilities specific to the region. Participants were then led through several exercises: first they identified climate change considerations for silvicultural planning and decision-making in the context of the silvics and disturbance ecology of the local forest ecosystems. In the afternoon, participants were divided into groups and completed a small-group activity in which they used elements of the Forest Adaptation Resources Workbook (Swanston and Janowiak 2012) to develop climate change adaptation tactics for a forest type of their choice. Breakout groups gave a summary report to the larger group toward the end of the day, with a synthetic wrap-up and evaluation concluding the 1-day training. The overarching goals of this training were to give participants usable tools for incorporating climate change considerations into management planning and to give them a chance to practice doing so in a learning environment fostering discussion and reflection.

The second and third days of the workshop consisted of just the expert panel of 10–20 managers and scientists. This portion of each workshop began with a visit to the prospective field site, with accompanying maps, inventory data, and site-level information in hand. Specific ecosystem vulnerabilities and climate change impacts were evaluated within the context of stand history, current conditions, and parameters of the local forest plan. Potential pitfalls and roadblocks of study implementation on the selected site were discussed, as were possible solutions. Participants were then divided into smaller groups to brainstorm ideas for the experimental treatments. Each group identified an appropriate set of DFCs and management objectives, both selecting from among existing objectives likely to remain important under climate change (such as timber production and wildlife habitat) and establishing new adaptation-related objectives in response to projected impacts and vulnerabilities (e.g., mitigate moisture stress and increase heat-tolerant species). An array of silvicultural tactics that correspond to each of the experimental treatments of resistance, resilience, and transition were then developed. Teaming managers with scientists in each group created an environment wherein participants were learning from each other, while producing scientifically sound, locally relevant, and operationally feasible potential approaches. The groups were encouraged to think broadly and creatively to allow the full range of possibilities to emerge and be considered.

The prescription development process used here may deviate from the process practitioners typically use, in which management objectives are primary to the articulation of a DFC. The experimental treatment options were defined a priori by the original science team as part of the common experimental design (Table 1), but the particular details of what each treatment consists of for a given forest type and how the individual treatment goals translate to site-specific management objectives are determined by the site expert panel.

Worksheets that walk through these prescription development steps within the framework of the national ASCC experimental goals and treatments designed by the science team were provided at each workshop. The final brainstorming of silvicultural tactics, including time frames, benefits, drawbacks, and recommendations, was also reported by small groups. Proactive facilitation by leaders of the national project guided consensus-building throughout the day toward a common set of DFCs, management objectives, and silvicultural tactics that likewise met experimental objectives in a compelling research framework.

The third and final day of each workshop began with a review and refinement of the DFCs, a comprehensive list of corresponding management objectives, and silvicultural tactics specific to resistance, resilience, and transition treatments. Complementary research questions of interest to a given site that could overlay on top of the ASCC framework were discussed at this juncture. Each workshop concluded with identification of any National Environmental Policy Act of 1969 (i.e., NEPA) or other planning needs, description of the common measurement plan for both pre- and posttreatment data collection including plot layout and measurements, implementation considerations and timeline, a data collection timeline, a clear description of next steps, roles, and responsibilities, and scheduling of follow-up meetings.

Additional Considerations

The long-term, collaborative, and forward-thinking nature of the ASCC project promises interesting and useful outcomes, no matter how individual treatments perform at each site. Long-term silvicultural trials have recently been used in new capacities to glean insights into how systems respond to change, even as the original study was designed to answer different questions (D'Amato et al. 2011, Camp et al. 2013). Although existing well-designed, long-term silvicultural trials can be remeasured to yield additional data and insights and can provide opportunities to evaluate models and vegetation response over time, there are often limitations to inferences that can be drawn, given the original study design and intent (i.e., treatment block or plot size, lack of replication, response variables historically measured, and others). We drew on both the experiences and findings of other long-term studies to conceive the overall ASCC project and, more specifically, to inform the silvicultural systems that were designed at each site to meet the treatment objectives (i.e., resis-

Figure 3. The Cutfoot Experimental Forest (EF) ASCC installation is located in red pine-dominated stands of the Chippewa National Forest (NF) in northern Minnesota. The San Juan NF in mountainous southwest Colorado hosts the ASCC site in mixed conifer forests whose dominant species change with elevation. The Jones Center installation at Ichauway, southern Georgia, focuses on mixed pine systems of the southeastern coastal plain. ASCC sites are being planned for western larch-dominated forests on the Flathead National Forest and the Coram Experimental Forest in northern Montana, and for a northern hardwoods forest at Dartmouth's Second College Grant, with a companion installation planned for Hubbard Brook Experimental Forest in New Hampshire.

tance, resilience, and transition). Long-term experiments such as ASCC are examples of a new generation of silviculture studies that are being deliberately designed and implemented at larger scales and with a higher degree of statistical rigor (i.e., replication), with treatments specifically designed to take into account current understanding about forest response to disturbance in the context of an uncertain future climate. These new studies will contribute significantly to the array of information available to managers into the future. Although there is great power in these multisite studies, even greater levels of commitment and resources from both the management and scientific communities are required to ensure that operationally relevant results are generated and translated into meaningful management options into the future.

Monitoring is a major component of the ASCC project, to be led by each site lead scientist. Responsibility for establishment of a permanent plot network, pre- and post-treatment data collection, and data archiving resides with the site lead scientist but must be conducted in a compatible way with the national ASCC minimum remeasurement standards to ensure intersite comparability in the future (Figure 2). A statistician familiar with the experimental design and project goals should be associated with each site to help maintain statistical rigor over time both within and among field sites (Ganio and Puettmann 2008). Because managers cannot wait for researchers to develop and test hypotheses around optimal solutions that may take years to identify, simulation modeling (e.g., using the Forest Vegetation Simulator) will be a major component of the project to test hypotheses in the short-term.

A recurring point of discussion in the development of the overall study design and during individual treatment development at each site was our evolving notion of DFCs with respect to the treatments. A paradigm for some decades on many national forests has centered on restoring ecosystems back to an ecological condition encompassed by the envelope of historical range of variability (HRV), with the rationale that these conditions will most likely yield healthy, resilient ecosystems (Keane et al. 2009). However, the notion of developing a DFC based on historical conditions has received scrutiny in the context of a changing climate as historical reference conditions may not represent appropriate future target stand structures (Millar et al. 2007, Millar 2014, Dumroese et al. 2015). Given the inherent uncertainty in climate change impacts across temporal and spatial scales, HRV may still hold some merit in informing (but not directing) silvicultural prescriptions (Keane et al. 2009) only if managers also incorporate insights from the best information available regarding probable future conditions and their distribution on the landscape. Looking forward as well as to the past could be especially useful when considering a variety of possible adaptation options akin to the ASCC approach. In any case, an emergent theme among the scientific community and practitioners alike is the notion that managing for a range of conditions, both spatially and temporally, while maintaining complexity in composition, structure, and function may be an effective way to enhance an ecosystem's ability to respond or adapt to future conditions (Franklin et al. 2007, Malmsheimer et al. 2008, Puettmann et al. 2009, O'Hara and Ramage 2013). The ASCC project provides an opportunity to test these notions across a broad spectrum of DFCs and management approaches for different forest types.

The five core ASCC project sites are in various stages of development (Figure 3). We will describe two sites that are currently at the most advanced stages of implementation: the Cutfoot Experimental Forest (CEF) site on the Chippewa National Forest in Minnesota, and the San Juan National Forest (SJNF) site in Colorado.

Site 1 Example: Cutfoot Experimental Forest, Chippewa National Forest

The first ASCC installation was installed on the USDA Forest Service's 3,000-ac CEF (latitude 47°40′N, longitude 94°5′W), located on the Chippewa National Forest in northcentral Minnesota, USA (Figure 3). The majority of the CEF supports forests dominated by red pine (*Pinus resinosa* Ait.) that is of natural fire origin circa 1918. The overstory contains lesser amounts of eastern white pine (*Pinus strobus* L.), red maple (*Acer rubrum* L.), trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marshall), balsam fir (*Abies balsamea* L.), northern red oak (*Quercus rubra* L.), and bur oak (*Quercus macrocarpa* Michx.). Historically, this ecosystem had a woodland structure due to fire, with patchy open (50–75%) canopy cover (Minnesota Department of Natural Resources 2003). At the time of study installation, stands were characterized by mostly closed canopies and basal areas of about 139 ft^2/ac (Palik et al. 2014).

Major Climate Change Projections

Over the last century, the region's climate has become modestly warmer and wetter (Handler et al. 2014). However, like many other regions, projections for future climate change are more extreme (based on Geophysical Fluid Dynamics Laboratory [GFDL] A1F1 model scenario). Average annual temperature by the end of the 21st century is expected to increase 8.8° F (com-

Table 3. DFCs and tactics for achieving them for the ASCC treatments on the CEF, Minnesota, and the SJNF, Colorado.

Treatment	CEF	SJNF
Resistance treatment: maintain relatively unchanged conditions	DFC Maintain red pine dominance (90% BA) Single cohort Reduced stocking closer to woodland structure Tactics Free thin to 100 ft^2/ac at first thinning Future thinning to 60 ft^2/ac	DFC Maintain current proportions of PP, DF, WF, aspen Tactics Reduce BA by 40–60% by thinning within 5 yr Retain priority PP > DF > WF Keep large PP/DF, old PP/DF/WF Even spacing
Resilience treatment: allow some change, eventual return to reference	DFC Red pine dominated (50–75% BA) Increase heterogeneity and structural complexity Increase native future-adapted species Tactics Variable density thinning (skips and gaps) 20% in 0.5-ac skips; 20% in 0.5-ac gaps Free thin matrix to 110 ft^2/ac Plant native future-adapted species in gaps, including eastern white pine, northern red oak, bur oak, red maple	DFC Increase drought-tolerant species Relative densities (% BA): 45–75% PP, 5–35% DF, 0–15% aspen, 0–10% WF Clumpy, multicohort structure Tactics Reduce BA by 40–60% by thinning Favor priority PP > DF > WF Create openings up to 1–3 ac (not for regeneration) Leave legacy groups, clumps Plant PP if compositional target is not met
Transition treatment: facilitate change, encourage adaptive response	DFC Reduce red pine dominance to 20–50%, multicohort structure Increase future-adapted species Tactics Expanding-gap irregular shelterwood 20% in 0.5-ac gaps Thin matrix to 70 ft^2/ac Plant future-adapted species in gaps and matrix: resilience treatment species, as well as novel species including white oak, bitternut hickory, black cherry, and ponderosa pine	DFC Increase drought-tolerant species Increase PP, allow RMJ to increase, open conditions Tactics Retain PP, aspen (on north slopes, swales) Remove all WF Canopy openness target of 30–40% Enhance current openings Increase shrubs for big game winter range Plant PP if compositional target is not met
Additional silvicultural tactics	Resilience and transition treatments: Site preparation in gaps with harrow disk	All treatments: Prescribe burn to raise canopy height and reduce ladder fuels Burn every 5–10 yr

BA, basal area; PP, ponderosa pine; DF, Douglas-fir; WF, white fir; RMJ, Rocky Mountain juniper.

pared with the 1971–2000 period), but with seasonally disproportionate temperature increases (9.8° F increase in winter, 5.4° F increase in spring, 11.4° F increase in summer, and 9.1° F increase in autumn). This model projects a slight decrease in average annual precipitation of -0.4 in. but a substantial decrease in summer annual precipitation of -4.8 in. Combining temperature and precipitation into potential evapotranspiration to precipitation ratios suggests slightly moister annual conditions by the end of the 21st century but substantially drier summer conditions, with the potential for greater drought stress during the growing season.

Potential Impacts and Expectations

When considering impacts during project scoping, we focused on projections in tree habitat suitability based on Tree Atlas (Prasad et al. 2007) and LANDIS II (Scheller et al. 2007) modeling results for Minnesota (Handler et al. 2014). The overall projection is that tree habitats in Minnesota will have shifted measurably to the northeast by the end of the 21st century. This will involve a decline in habitat for most of the boreal tree species typical of the study ecosystem, an increase in habitat for several of the associated north temperate tree species and increased habitat for several tree species new to the region. The interactive effects of climate on important disturbance agents, including *Armillaria* root disease and bark beetles, were also considered in evaluating future climate impacts on tree habitats.

Workshop participants examined these tree habitat projections and also assessed the current condition of the selected forest type (overly dense, fire excluded) to justify their decision on study location. The overarching sentiment was that the forest is vulnerable to climate change, on the cusp of major change in tree species composition and may face a host of related forest health issues as a result of these changes.

ASCC Treatments

Workshop participants spent a day and a half discussing and developing treatments for the project, as described in the Workshop and Experimental Design Process. In addition to Tree Atlas and LANDIS II modeling, the treatments were also informed by results from several long-term silvicultural studies in the CEF, as well as key attributes of DFCs (Table 3).

The *resistance treatment* (Table 3; Figure 4) is designed to preserve mature red pine into a future of warmer, drier growing seasons. The intent is to maintain red pine as the dominant species, but thin stands periodically to reduce the negative impacts of drought on productivity and health by maintaining density near the lower level of acceptable stocking (B-line) (Gilmore and Palik 2005). There is mounting empirical evidence that maintaining red pine stands near the lower level of stocking is effective for reducing drought impacts on growth (D'Amato et al. 2013, Bottero et al. 2017). However, we recognize that this treatment is unlikely to maintain red pine indefinitely, should conditions become unfavorable for establishment.

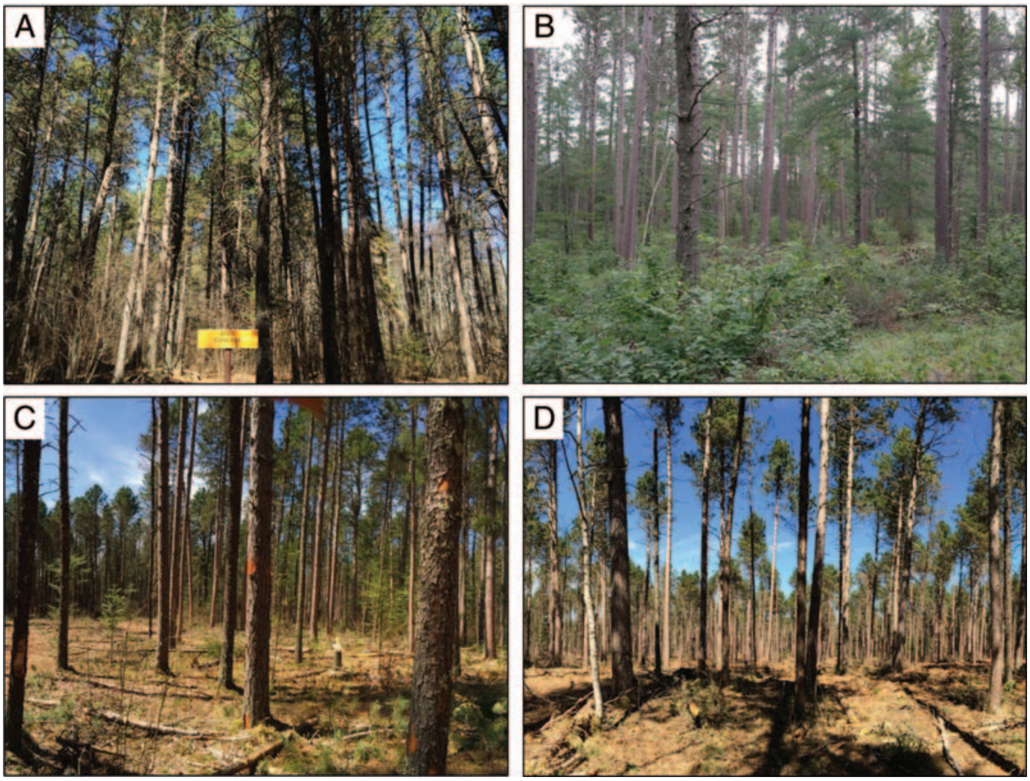

Figure 4. Photos showing four treatments on CEF in Minnesota: no action control (A), resistance (B), resilience (C) (with gap on left-hand side of photo, thinned matrix on right-hand side), and transition (D) treatments. (Photos courtesy of Eli Sagor, 2015.)

The *resilience treatment* (Table 3; Figure 4) is a strategy to move beyond red pine as the dominant species but still maintain a species composition within the HRV. The focus is on species that are native to the ecosystem and are predicted to have increased habitat suitability under a future climate. Eastern white pine is a key species for this strategy. It can be locally abundant and is tolerant of a wide range of competitive environments (Montgomery et al. 2013). The tactic for this treatment involves a hybrid variable density thinning/retention harvesting approach, with future actions to facilitate regeneration of a suite of desired species. Such an approach provides localized open environments for recruiting future-adapted species, yet maintains considerable mature canopy structure across the stand to ameliorate understory microclimate conditions and sustain a diversity of habitats.

The *transition treatment* (Table 3; Figure 4) is based on the premise that habitat suitability will be maintained for some species (i.e., those included in the resilience treatment) but that there will be increasing opportunities for new species to become established. The inclusion of some of these additional species, including white oak (*Quercus alba* L.), bitternut hickory (*Carya cordiformis* Wangenh. K. Koch), and black cherry (*Prunus serotina* Ehrh.), is based on Tree Atlas modeling, which projects modest increases in their habitat suitability (Handler et al. 2014).

The transition treatment is also based on the belief that there will be a desire among stakeholders to maintain a forest that bears some resemblance to the current condition. To this end, the treatment includes planting ponderosa pine (*Pinus ponderosa* Dougl.), a species with stature, morphology, and ecological characteristics similar to those of red pine, but with greater drought tolerance. Ponderosa pine, while novel and nonnative to the region, is widely planted in central and northern Minnesota as a landscape tree. Moreover, long-term results from a provenance study of ponderosa pine (Radsliff et al. 1981) suggest that seed sources from the eastern part of the range (Nebraska, western South Dakota, and eastern Montana) that best match the elevation of the CEF study site may have reasonable levels of survival and growth. The expanding gap irregular shelterwood system used for the transition treatment (Table 3) also reflects the desire to progressively shift composition on these sites to greater representation of ponderosa pine and other future-adapted species, with initial entries focused on establishing a broad suite of species across gap and matrix environments.

Progress and Activities

Treatments were implemented on the CEF ASCC installation in winter 2014–2015, with ongoing research and management activities planned for at least the next 10 years. Although in its infancy, the project has already served as a focal point for several tours and training sessions, including the National Advanced Silviculture Program, a University of Minnesota climate change summit, the Minnesota Society of American Foresters 2015 and 2016 summer meetings, and the Forest Stewards Guild 2016 national meeting. The experiment was featured as part of a Minnesota Public Radio piece on climate change. Plans for the future include hosting a tour for the 2016 Silviculture Instructors Tour and several future meetings.

Site 2 Example: San Juan National Forest, Colorado

Study Site

The San Juan ASCC study was established on Jackson Mountain in the SJNF in southwestern Colorado, USA (latitude 37°21′N; longitude 106°56′W) (Figure 3). The area has a mean annual precipitation of about 24 in., dominated by snow from November to March and monsoonal moisture in the summer months. Mean annual temperature is approximately 42° F, with 30-year maximum (July) temperatures of 81° F and minimum (January) temperatures of 5.5° F, respectively (PRISM Climate Group 2014). Soils are very deep, well drained, and loamy. The study area ranges in elevation from 7,400 to 8,600 ft, with dissected deep drainages, multiple aspects, and slopes from 0 to 35%.

The site is a warm/dry mixed conifer forest consisting of ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelmann), Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco), white fir (*Abies concolor* [Gordon and Glendinning] Lindley ex Hildebrand), aspen (*Populus tremuloides* Michaux), and a shrubby component of Gambel oak (*Quercus gambelii* Nuttall). Before 1873, mean fire interval was about 30 years (Korb et al. 2013). The area was lightly logged 50–60 years ago as indicated by large ponderosa pine stumps. In the mid-1970s a prep cut of a two-stage shelterwood was implemented. Over the past several decades, the area has been subjected to a range of insects such as western pine beetle (*Dendroctonus brevicomis* LeConte), fir engraver (*Scolytus ventralis* LeConte), and Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins), as well as root disease, fir broom rust (*Melampsorella caryophyllacearum*), and dwarf mistletoe (*Arceuthobium* spp). Pretreatment basal area was approximately 139 ft^2/ac, dominated by a mixture of ponderosa pine, Douglas-fir, and white fir in the overstory, with white fir and Gambel oak in the understory (Figure 5).

Major Climate Change Projections

Over the past several decades, Colorado has seen an increase in annual average temperature of 2.0° F, with daily minimum temperature increasing more than daily maximum temperatures (Lukas et al. 2014). Snowpack has decreased, and the timing of snowmelt and peak runoff has shifted earlier in the spring. In addition, the frequency of more severe droughts, as measured by the Palmer Drought Severity Index, has increased (Lukas et al. 2014). By the mid-21st century, the average annual temperature in the San Juan mountain region is expected to increase by 4.0° F (compared with the 1971–2000 period) with a 3–4° F increase in the winter and a 4–5° F increase in the summer. Projected changes in precipitation are more difficult to determine because of the complex topography and wide HRV between 1971 and 2000. Besides May, most of the median changes in precipitation are not more than a 10% change from the 1971 to 2000 measurement period. However, based on the projected increase in temperature during the winter months, less of the annual precipitation will fall as snow and more of the snowpack will melt earlier (Lukas et al. 2014).

Potential Impacts and Expectations

To identify climate impacts during the SJNF workshop, we considered information presented in a vulnerability assessment for the San Juan mountain region (Decker and Rondeau 2014). The vulnerability assessment incorporated factors such as elevation, bioclimatic envelopes, biological stressors, dispersal rates, and vulnerability to increased frequency and intensity of extreme events. Because warm/dry mixed conifer forests have tree species that have overlapping bioclimatic envelopes and are often within the transitional ecotone area between ponderosa pine forests at the lower elevations and spruce/fir forests at the higher elevations, the vulnerability to climate change is difficult to ascertain. The diversity of coexisting tree species that can establish and grow together gives this ecosystem a variety of advantages in the face of climate change. Because earlier snowmelt lengthens the wildfire season, it is expected that wildfire frequency will increase in the future (Westerling et al. 2006). Changes in climate are also expected to increase bark beetle outbreaks (Bentz et al. 2010). Therefore, future stand composition will be a result of the interactions of changing climate and fire, drought, insect outbreaks, and pathogens. Each species has a different susceptibility to these disturbances (Table 4), and therefore novel species compositions or changes in species dominance are possibilities.

ASCC Treatments

Workshop participants considered the current condition of the forest to be unsustainable because of the shift in species composition and increase in density compared with the historical conditions that were regulated by a frequent fire regime (Fule et al. 2009, Korb et al. 2012, 2013). This initial forest condition was an issue that required additional discussion about the ASCC treatments, particularly the resistance and resilience treatments. For both of these treatment types, participants acknowledged that a reduction in density was necessary as a starting point for any discussion of desired future conditions. Once agreement on the amount of density reduction and which species to favor was reached, then ASCC treatment tactics and maintenance were discussed.

The *resistance treatment* (Table 3) was designed to preserve similar species composition but reduce overall density. The resilience treatment attempts to maximize growing space by creating uniformly spaced canopy cover and basal area throughout the stand and reducing ladder fuels. These actions intend to mitigate the impacts of drought on productivity and to reduce fire hazard in the stands. Future management activities in this treatment will attempt to maintain the proportions of each tree species, but at the reduced densities established in the first entry.

The *resilience treatment* (Table 3) was designed to create an open forest structure resistant to fire and drought composed of thick-barked, long-lived, and shade-intolerant tree species with a range of tree ages and sizes and variable tree spatial patterns. The participants used research from local HRV studies (Fule et al. 2009, Korb et al. 2013) to inform the desired outcome of the first entry activities. As a starting point, density will be reduced substantially, but residual species composition will favor ponderosa pine and Douglas-fir over white fir. Furthermore, to increase resilience to fire, smaller-diameter Douglas-fir and white fir will be preferentially removed, whereas ponderosa pine will be retained. Residual trees to be retained will promote spatial complexity in groups of trees and individual trees within a matrix of openings of various sizes up to 2 ac (*sensu* Larson and Churchill 2012). Average basal area targets were 56–78 ft^2/ac but allowed for a range between 0 and 122 ft^2/ac. Future management activities will attempt to promote ponderosa pine and some Douglas-fir regeneration, maintain spatial complexity, and discourage white fir regeneration.

The *transition treatment* (Table 3) considers that the current forest structure and species composition will have limited future suitability at the study site's elevation. This treatment focused on facilitating upward-moving dominance of the species present at lower elevations on the SJNF such as ponderosa pine, juniper, and other shrubs. Residual basal area was on average 40 ft^2/ac, with a range of 0 to 78 ft^2/ac. In this treatment, all white fir were removed, target canopy openness was around 30–40%, and large openings were prevalent.

For all three treatments, prescribed fire will be implemented every 5–10 years to reintroduce frequent fire disturbance, maintain sustainable densities of tree regeneration, and return other ecological processes important to this ecosystem.

Progress and Activities

Pretreatment forest inventory surveys to inform marking guidelines have been completed on the San Juan ASCC study site. The research stands have been marked for harvest and are scheduled to be cut in the next few years. Future inventories will focus on installation of additional permanent plots, establishment of a forest health survey, soil sampling, and inventory of fuels and understory plants.

Lessons Learned

As for all endeavors of this magnitude, communication that comes early and often is the key to success. All partners were engaged early in the study development process and continue to be engaged on at least a monthly basis. Another important aspect of this collaboration is the layered communication and engagement of researchers with managers to ensure that site layout, tree cruising and marking, harvesting, and postharvest inspections meet the goals of the experimental treatments. The ASCC treatments may in some cases push the envelope of experience for the managers involved, making this kind of collaboration critical for successful implementation.

Another challenge facing implementation of large-scale, multisite silvicultural research is that not all regions of the United States have equally viable timber industries. Consequently, it may be a challenge in some regions to implement timber harvesting treatments on the scale of the CEF harvest or to fund regeneration activities if timber receipts from the project itself are not available to fund the activities (as is the case for the SJNF).

Given the limited experience of many parties in operationalizing adaptive silviculture techniques, the selection of ASCC sites was informed at least in part by their accessibility for field trips, public outreach, and training. The locations were selected to include an excellent example site that facilitates broad and rich discussion, shows concrete examples, and will be an invaluable tool for years to come as data are collected and we learn from the study.

Figure 5. Representative photo of current conditions at the SJNF site in Colorado. (Photo courtesy of Steven Hartvigsen, 2014.)

Future Directions

Several additional ASCC installations are underway in Georgia, Montana, and New Hampshire (Figure 3), including both public and private lands. Measurements are ongoing on the CEF and SJNF sites, with pretreatment data collection beginning at other sites. Additional phases of the study will involve immediate posttreatment data collection on regeneration and ground layer vegetation response and simulation modeling based on the treatments designed at each site. Plans for intersite analysis of both simulation results and field data are in development. Presentations and field tours for local, regional, and national audiences of managers and scientists will continue, and future phases of the project may include development of additional sites, depending on funding.

Conclusions

Through this article we described the climate change framework we used with a manager-scientist partnership to apply forest adaptation concepts to different forest ecosystems at a variety of locations as part of the ASCC study, we presented a set of questions and working hypotheses that will help iden-

Table 4. Tree species within the warm/dry mixed conifer forests of the SJNF and the tolerance to drought, heat, and fire.

Species	Drought[1]	Heat[2]	Surface fire[2,3]	Insects[4]
Ponderosa pine	Tolerant	Tolerant	Seedlings susceptible	Mountain pine beetle; *Ips*
Douglas-fir	Intermediate	Intermediate	Seedlings and saplings susceptible	Western spruce budworm; Douglas-fir tussock moth; Douglas-fir beetle
White fir	Intolerant	Intermediate	Seedlings, saplings, and poles susceptible	Western spruce budworm; Douglas-fir tussock moth; fir engraver
Aspen	Intolerant	Intermediate	Sprouter	Tent caterpillar; aspen bark beetle
Gambel oak	Tolerant	Tolerant	Sprouter	Tent caterpillar; wood borers

Listed insects are those that have potential to negatively impact the specific tree species.

[1] Niinemets and Vallardes (2006).

[2] Minore (1979).

[3] Jain et al. (2012).

[4] Rocky Mountain Region, Forest Health Protection (2010).

tify which adaptation options and associated silvicultural systems best meet current and future management goals, and we gave a broad overview of how we implemented this approach at two different sites to illustrate the types of considerations one might need to think about in designing a study of this nature.

As conceived, the ASCC project will provide examples of adaptation strategies that span not only a range of options but also a range of comfort levels and acceptability by managers. Some approaches are already found in the toolbox (e.g., resistance treatment at the CEF), but other approaches may push the envelope of traditional management approaches and experience, given current climate and social contexts (e.g., transition treatment on the CEF). However, by using the process and framework described above, we feel that all of the ASCC treatments have broader buy-in than would occur if researchers developed them in isolation of managers. Moreover, they provide an array of working hypotheses regarding strategies for sustaining our nation's ecosystems similar to those put forth by the scientists developing early silvicultural trials in US forests at the turn of the last century. In addition, the interactive process allows us to directly address the numerous barriers natural resource managers face when it comes to developing adaptive forest management strategies for climate change, thereby giving the strategies broader and more realistic applicability.

Endnote

1. For more information, see www.forestadaptation.org.

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