

Ten Years of Adaptive Silviculture for Climate Change: An Applied, Coproduced Experimental Framework

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Climate change presents challenges for forest managers in determining strategies and actions to enable forest ecosystems to adapt to rapid and uncertain change. The Adaptive Silviculture for Climate Change (ASCC) Network emerged in direct response to an acute need for experimentally robust and professionally credible examples of climate-adaptive forest management strategies. The ASCC Network advances the field of climate adaptation by applying a replicated resistance–resilience–transition and no-action framework to test coproduced, operational-scale experimental trials that incorporate locally specific desired future conditions and adaptation tactics, tailored to different forest types. It exemplifies timely, practical, and scientifically rigorous application of climate adaptation actions while fostering manager–scientist collaboration. Given the collaborative framework, outcomes from the experimental treatments can directly inform local management actions for practitioners now and into the future while serving as a model framework for coproduction of adaptation science applicable to other contexts and ecosystems.

Keywords: adaptation, forest management, resistance, resilience, transition

Climate change is leading to unprecedented ecological change across diverse geographies and ecosystems, amplifying the need for actions that sustain ecosystem health and services (Pörtner et al. 2022, Domke et al. 2023, McElwee et al. 2023). Given the key role that forests play in provisioning ecosystem services, mitigating greenhouse gas emissions, and supporting cultural values, increasing attention has been paid toward actions that maintain or promote forest health and function during a period of unprecedented and uncertain global climate change (Himes et al. 2023, Schattman et al. 2024). As such, many land management and conservation organizations are placing increased emphasis on management actions to help ecosystems adapt to interacting and compounding stressors, including extreme precipitation, drought, and wildfires, and to mitigate greenhouse gas emissions associated with ecosystem disturbance (Dale et al. 2001, Wasley et al. 2023). Although the adaptation and mitigation potential of forests is well recognized as critical to ensure the provision of diverse ecosystem services (Fargione et al. 2018, Domke et al. 2023), implementation, monitoring, and demonstration of adaptation approaches lags the pace of climate change but is paramount to responding to future challenges (Wasley et al. 2023).

Numerous conceptual and practical frameworks, collaboratives, and compendia of adaptation strategies have evolved to address the need for holistic approaches to climate-informed ecosystem management (Millar et al. 2007, Swanston et al. 2016, Halofsky et al. 2018, Peterson St-Laurent et al. 2021, Schuurman et al. 2022, among many others). In forested ecosystems, a grow-

ing literature examines management strategies that collectively support ecosystem-based climate adaptation, mitigation of greenhouse gas emissions via carbon uptake and storage in forests, and the continued provision of ecosystem benefits for societal needs (e.g., Ontl et al. 2018, Bowditch et al. 2020, Weatherall et al. 2022, Cooper and MacFarlane 2023), despite apparent trade-offs in some management contexts (Littlefield and D'Amato 2022). At the same time, there are significant gaps in both the application of adaptation practices in land management, particularly given the increasing pace of and attention to climate change (Himes et al. 2023, Wasley et al. 2023, Schattman et al. 2024) and how to evaluate the effectiveness of adaptation actions that are implemented (Seidl et al. 2016, Weatherall et al. 2022). Notably, effective forest adaptation requires the implementation of on-the-ground actions designed to elicit changes in composition, structure, and ecosystem function to achieve desired future conditions; these actions are all encompassed within the discipline of silviculture (Palik et al. 2020). Silviculture has a long-standing role in managing forests for diverse ecosystem services and societal benefits (Puettmann et al. 2009, Deal 2018) and responding to changing drivers of forest change, making it highly relevant to discussions of climate change adaptation (box 1).

The Adaptive Silviculture for Climate Change (ASCC) Network was created in 2009 and designed and established over the following years to evaluate and advance the understanding and implementation of climate adaptation in managed forests (Nagel et al. 2017). The ASCC Network advances a coproduced, opera-

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Box 1. The role of silviculture in climate change adaptation.

Silviculture as a discipline developed historically out of wood scarcity in the nineteenth century with early forest scientists applying plant and soil science principles to develop strategies for sustaining a harvestable wood crop from natural and planted forests (Puettmann et al. 2009). Aspects of these historical roots are apparent in current definitions of the field, which define *silviculture* as “the art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society” (Deal 2018). Nevertheless, there have been significant shifts in the discipline of silviculture over the past several decades from this emphasis on top-down control of forest conditions toward greater integration of ecological, social, and cultural values and dynamics (Puettmann et al. 2009). This includes recent calls to recast silviculture as a field that “supports and stewards forest and woodland ecosystems and their ability to adapt” (Puettmann et al. 2025). This evolution has demonstrated silviculture’s ability to be highly adaptable to changing conditions including diverse social, economic, and ecological drivers of change (Achim et al. 2022, DeRose et al. 2024), with climate-adaptive silviculture as an example.

Inherent to contemporary silviculture is the process of clearly defining desired future conditions, and then planning and implementing actions to direct ecosystem development to achieve those conditions. Desired future conditions express the ecosystem conditions that are preferred by stakeholders and managers (Landres et al. 1999, McComb 2007) in terms of target forest composition, age structure, tree size distributions, and other forest qualities. Although prescriptive in desired outcomes, the uncertainties in the timing and extent of changes in climate at a specific location, combined with uncertainty of forest responses to those changes, necessitate an adaptive approach (D’Amato et al. 2023a, D’Amato and Palik 2021, Achim et al. 2022) that is specifically tailored to anticipated future climate conditions. This may include altering species composition to favor climate-adapted species (Palik et al. 2022) or using structural targets (i.e., tree densities, spatial arrangements, and age structures) to promote conditions less vulnerable to drought, wildfire, or wind (Churchill et al. 2013, Polinko et al. 2022). As with other ongoing adaptation efforts, acknowledging and embracing climate uncertainty is a hallmark of the process by which silviculture will incorporate climate change (Millar et al. 2007), with attendant adjustments over time to planning and expectations (Janowiak et al. 2011, Achim et al. 2022, DeRose et al. 2024). In many cases, this may be a significant shift from the historical emphasis of silviculture and forest management planning, which often operates under an assumption that ecosystem dynamics can be controlled by management interventions to generate predictable outcomes. The following outlines some key elements that managers consider when incorporating a climate-adaptive response into forest management planning. These elements and other considerations for intentionally addressing uncertainty are integrated and tested through the ASCC experimental framework. Some considerations for climate-adaptive silviculture are described below.

Changing habitat suitability. The tree species favored by silvicultural activities have historically emphasized species and genotypes adapted to local site conditions, including soils, climate, and disturbance regimes. Selection of species has largely been based on adaptation to historical conditions at a given locale; however, a consideration specific to climate change is whether habitat suitability for tree species of interest, either those currently in the forest or those desired to be, has the potential to change within a timeframe encompassed by the silvicultural prescription, which is the collection of treatments a forester uses over time to achieve desired outcomes. This challenge has led to the concept of forest assisted migration (Pedlar et al. 2012, Palik et al. 2022), where species or genotypes are deliberately moved to sites projected to remain or become suitable under future climate conditions, thereby aligning management decisions with anticipated ecological change. As a result, the use of decision-support tools that leverage maladaptation genomics (Aitken et al. 2008, Aitken and Whitlock 2013) and species distribution models (Iverson et al. 2019, Peters et al. 2019) to project future seedlot selection zones and species habitat distributions under future climates are increasingly being used to guide the species and genotypes encouraged by climate-adaptive silviculture (Peters et al. 2020, St. Clair et al. 2022, Stewart et al. 2022). In addition, desired future conditions increasingly include a greater emphasis on favoring mixtures of species and genotypes as a portfolio approach that spreads risk of future maladaptation and vulnerability (cf. Crowe and Parker 2008).

Changing threats. Reducing the impacts of stressors and disturbance on tree growth and mortality has long been a central goal of silviculture given the historic emphasis on sustaining a harvestable wood crop. This has included treatments designed to increase vigor of desired trees through reducing levels of resource competition (e.g., weeding, thinning) and proactive strategies to anticipate mortality through targeted removal of lower vigor individuals or species susceptible to a given threat. Nevertheless, increases in the severity and frequency of numerous threats under a changing climate, including extreme weather events, insect pests and pathogens, and wildfire may challenge the effectiveness of these strategies calling for a more climate-adaptive approach. This may include shifting desired stand conditions from a historic emphasis on full site occupancy with commercial species to those that emphasize reducing vulnerability to future stressors and enhance recovery of key ecosystem service provisioning. For example, warmer, drier growing seasons may increase the risk of catastrophic wildfire, warranting increased attention to fuel reduction treatments in overly dense forests that shift closed-canopy forests to more open, woodland conditions (Churchill et al. 2013). Similarly, the increasing proliferation of nonindigenous insects and pathogens will require climate-adaptive strategies that encourage mixtures of functionally redundant species to offset the impacts of species loss on key ecosystem functions and values (cf. Messier et al. 2013). Overall, these increasing threats will likely push climate-adaptive silviculture toward strategies that emphasize heterogeneity at multiple scales, both in terms of structural conditions managed for and compositional conditions encouraged.

Changing societal expectations. Climate-adaptive silviculture, like past evolutions of the field, is centered on sustaining the values forests contribute to society. These values and overall societal expectations of desired ecosystem services may change in the face of climate pressures and societal and ecosystem responses. For example, carbon sequestration in forest ecosystems and wood products are services long provided by forests and industry, but increased understanding of their role in slowing the rate of global warming has led to the development of strategies and practices for intentional carbon stewardship and sequestration (Ontl et al. 2019). At the same time, aesthetic values tied to forest conditions threatened by climate impacts (e.g., mature forests in fire-prone landscapes) or cultural values linked to a threatened species may motivate widespread and novel application of practices to sustain these values into the future (D'Amato et al. 2023b, Davis et al. 2024). Central to sustaining societal values is an acknowledgement of the limits of silvicultural interventions in counterbalancing all future negative climate impacts. Instead, climate-adaptive silviculture is an approach that can directly support the adaptive capacity of ecosystems in ways that can sustain a diversity of ecosystem services in a dynamic and rapidly changing environment.

Box 2. Adaptation treatments: resistance, resilience, and transition.

The ASCC study design consists of three active management treatments—resistance, resilience, and transition—and a no-action control that provides a passive approach to adaptation (i.e., no management intervention, let nature take its course; see table 1 for definitions). This provides a robust and consistent framework across installations for evaluating a range of forest management (i.e., silvicultural) interventions for climate change adaptation. The reference point for all treatments is typically the starting forest condition at the onset of the experiment, which varies among installations, but generally is not considered to be optimally positioned to adapt to climate changes. In other words, the current condition may be vulnerable to the present and anticipated effects from climate change.

When the ASCC project was initiated in 2009, collaborators developed the experimental framework using treatments for resistance, resilience, transition (table 1, figure 1) by adapting terminology from Millar and colleagues (2007) that was already in use among forest managers (Janowiak et al. 2011, Peterson et al. 2011, Swanston et al. 2016). This framework has been successfully used to support adaptation planning with natural resource managers in various settings to meet diverse management objectives (Janowiak et al. 2014, Swanston et al. 2016, Ontl et al. 2018) including the development of more than 500 adaptation demonstrations through the Climate Change Response Framework (CCRF, www.forestadaptation.org). Other conceptual frameworks for adaptation have been developed to describe the range of management options available to land managers as a way to help support decision making (e.g., Peterson St-Laurent et al. 2021) including the resist–accept–direct framework that outlines a range of adaptation options in response to transformational change (Schuurman et al. 2022). The strength of the resistance–resilience–transition framework is the intent and direction of adaptation actions relative to the starting condition, creating a framework for comparing the efficacy of different actions in working toward management goals and desired future conditions. The ASCC Network installations are diverse in forest types, historical disturbance regimes, and management contexts, so the development and application of resistance–resilience–transition adaptation treatments is conditional and informed by these starting points.

tional scale (i.e., at a meaningful spatial scale to a forest manager and representative of regional management practices), replicated experiment designed to test a suite of adaptation actions across multiple regions and a diversity of North American forest types. The ASCC Network currently consists of 14 installations in the United States and Canada occurring in nine important forest types, collectively covering over 2000 hectares (ha; www.adaptivesilviculture.org). Each installation tests and demonstrates an array of adaptation options with the intent to provide forest managers with tangible examples of climate adaptation and an evaluation of the efficacy of different interventions through a diversity of response variables over time. The ASCC installations use a robust experimental framework to evaluate adaptation treatments designed to promote resistance, resilience, or transition (three active management scenarios) to climate change impacts (see box 2 and table 1 for treatment descriptions and definitions; Millar et al. 2007, Swanston et al. 2016, Nagel et al. 2017). Each installation also includes a no-action treatment to demonstrate the efficacy of a passive management approach to climate change, which also serves as an experimental control.

The ASCC installations have been at the forefront of science coproduction for adaptation (Enquist et al. 2017) and are actively

developed and maintained through partnerships between forest managers, research scientists, and local partners. By using a common experimental framework across diverse sites, the ASCC Network brings a much-needed level of scientific rigor to the emerging field of climate adaptation practice in forest ecosystems, providing important insights and lessons applicable to the growing communities of practice engaging in adaptation. After more than 10 years of development, the ASCC Network has notably advanced climate adaptation at different scales via several avenues. In the present article, we highlight the ASCC Network as a leading effort within the growing field of climate change adaptation and describe its development and progress toward the following four goals: to develop and implement an experimental framework testing a suite of replicated climate-adaptive management actions with practical, real-world relevance that meet place-based management objectives and contexts across a diversity of forest ecosystem types; to evaluate and compare intentionally designed silvicultural treatments of resistance, resilience, and transition to identify forest management interventions that facilitate climate change adaptation over time at individual sites, enabling multisite comparisons; to foster collaborative science–management partnerships through a coproduction framework to address com-

Table 1. Resistance–resilience–transition framework including treatment definitions, advances in applying adaptation pathways, and expected outcomes.

Attribute	Resistance	Resilience	Transition	No action (control)
Experimental treatment definitions (<i>sensu</i> Nagel et al. 2017)	Actions that improve the defenses of the forest against anticipated change or directly defend the forest against disturbance to maintain relatively unchanged conditions	Actions that accommodate some degree of change, but encourage a return to a prior condition or desired reference conditions after disturbance	Actions that intentionally accommodate change and enable ecosystems to adaptively respond to changing and new conditions	Given that climate change impacts all forests globally, under the “no action” forests are allowed to respond to climate change in the absence of direct silvicultural intervention as an appropriate baseline
Advances in application of adaptation pathways derived from ASCC experience	Designed to respond to specific climate impacts Desired condition may become more vulnerable over time Assumes greater risk of not meeting desired future conditions with altered climate conditions	Supports the inherent ability of the ecosystem to change and reorganize within a defined range of reference conditions May be informed by natural or historical range of variation Provides a widening range of options to reduce risk compared to resistance	Enhances capacity of the ecosystem to change to a new state Actively facilitates change, often transforming to a novel system Assumes greater risk in the near term to reduce long-term risk May be most relevant to highly vulnerable systems already transforming	Ecosystem is allowed to respond passively to climate change without direct silvicultural intervention Risk is a function of climate and environmental changes
Examples of expected outcomes	Maintain soil moisture availability for remaining trees by reducing stocking (thinning) Maintain growth during drought and other stressors Enhance defenses to disturbance Maintain existing vegetation community	Complex age or size structures and species mixtures that increase the range of functional responses to climate and disturbance Native adapted tree species increase in abundance	Enhanced range of resource and environmental conditions Increase abundance of future-adapted species and genotypes (including novel) Novel species potentially replace native species	Declining growth and increased mortality of nonadapted species Potential conversion to undesirable state, including a nonforested state

Note: The baseline for comparison is the condition at the time of installation. Modified from Nagel et al. 2017.

plex and novel challenges, ultimately leading to greater direct actionable science delivery and implementation of climate-adaptive management actions; and to provide valuable insights to the broader community of researchers, managers, and others actively engaged in efforts to bolster ecosystem adaptation and climate-informed land management to the benefit of society and the environment.

In this article, we describe the experimental and coproduction framework we used to build a robust network of experimental field sites testing forest ecosystem adaptation in a real-world context. Concurrently, we describe emergent trends and perspectives of success and outline broader outcomes and impacts of the ASCC manager–scientist collaboration. We conclude the paper by synthesizing core principles we’ve learned through a decade of experience, with an emphasis on tailoring the framework to broader regional and environmental contexts.

ASCC experimental framework

This work began in concert with wider calls for the need for coproduced science to address climate change impacts on global ecosystems (Lemos and Morehouse 2005) and likely represents the first coproduced network of a gradient of adaptation concepts in a robust experimental design. The strengths of the ASCC project are rooted in a common set of core criteria that makes the network distinct from other long-term silviculture and climate-adaptive ecological research experiments.

At the genesis of the project, a group of thought leaders working at the intersection of climate adaptation and silviculture from across the United States convened over the span of 2 years to build a robust and replicable experimental and science delivery framework, including working definitions of climate adaptation concepts (i.e., resistance, resilience, transition, and no action; box

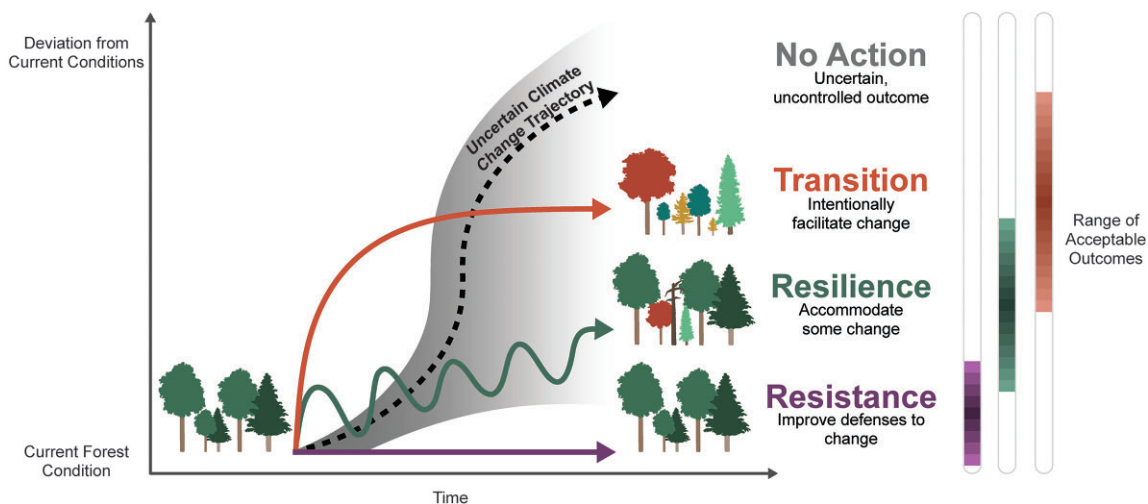


Figure 1. Conceptual diagram of the resistance–resilience–transition framework applied to the ASCC Network, positioned vertically along a spectrum of ecological persistence to change (i.e., adaptation). The y-axis presents the degree of alignment with current conditions relative to the future range of acceptable outcomes (i.e., desired future conditions). Graphic: Kailey Marcinkowski.

ASCC Network Leadership and Coordination Each Installation Meets Network Experimental Design Criteria

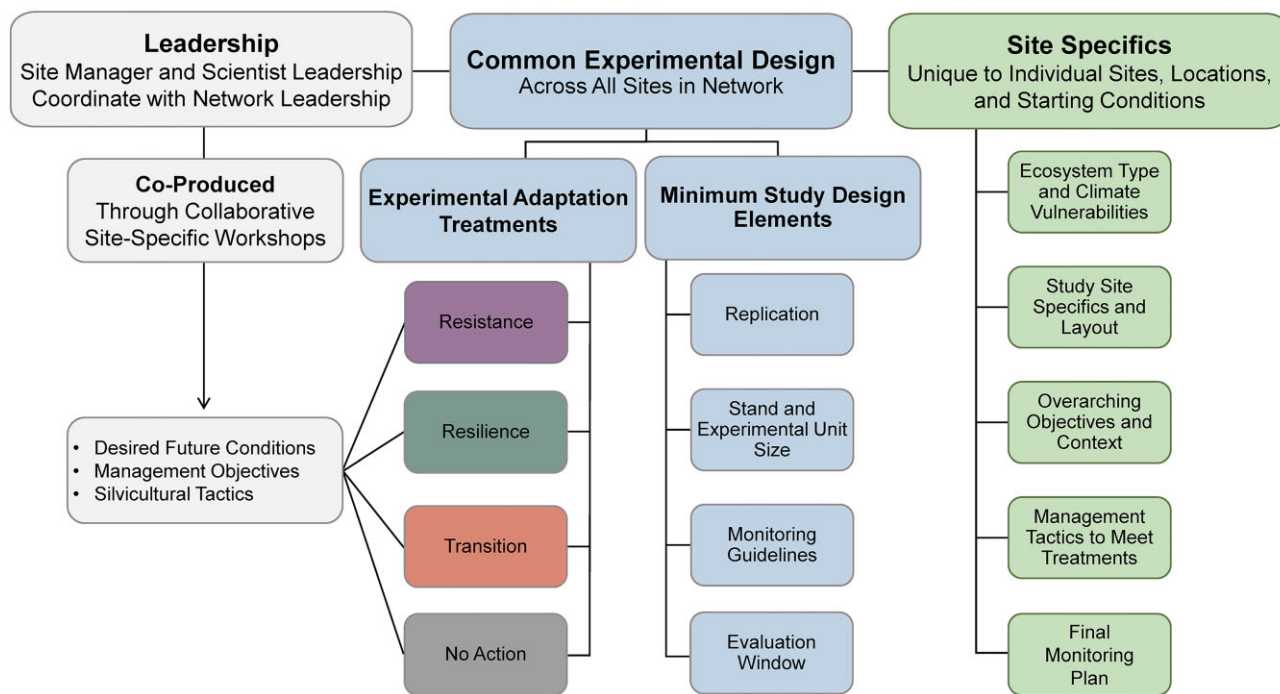


Figure 2. The Adaptive Silviculture for Climate Change (ASCC) Network experimental design showing coordination of the network, leadership of each site, experimental design criteria that are consistent across all sites, and site specific attributes that are unique for each site.

2, table 1) specific to forests, and core experimental design elements such as treatment unit size, replication, monitoring criteria. We then created a collaborative process that brings together scientists, local natural resource managers, and community partners to develop, implement, evaluate, and demonstrate climate-adaptive silviculture treatments (figure 2).

The ASCC approach centers around a workshop of local scientists and land managers, where the overarching goal is to build consensus while developing the silviculture treatments that will

achieve the goals of resistance, resilience, and transition for the local forest. The process begins with establishing the forest conditions at the time of the workshop as the baseline condition, which is subsequently evaluated as an experimental reference point. In most cases, the baseline conditions and reference point will be the same, but the reference point may differ slightly in some highly degraded stands that require intervention to stabilize progressive decline. The next major step is to articulate a defined set of desired future conditions, management goals and objectives, and locally

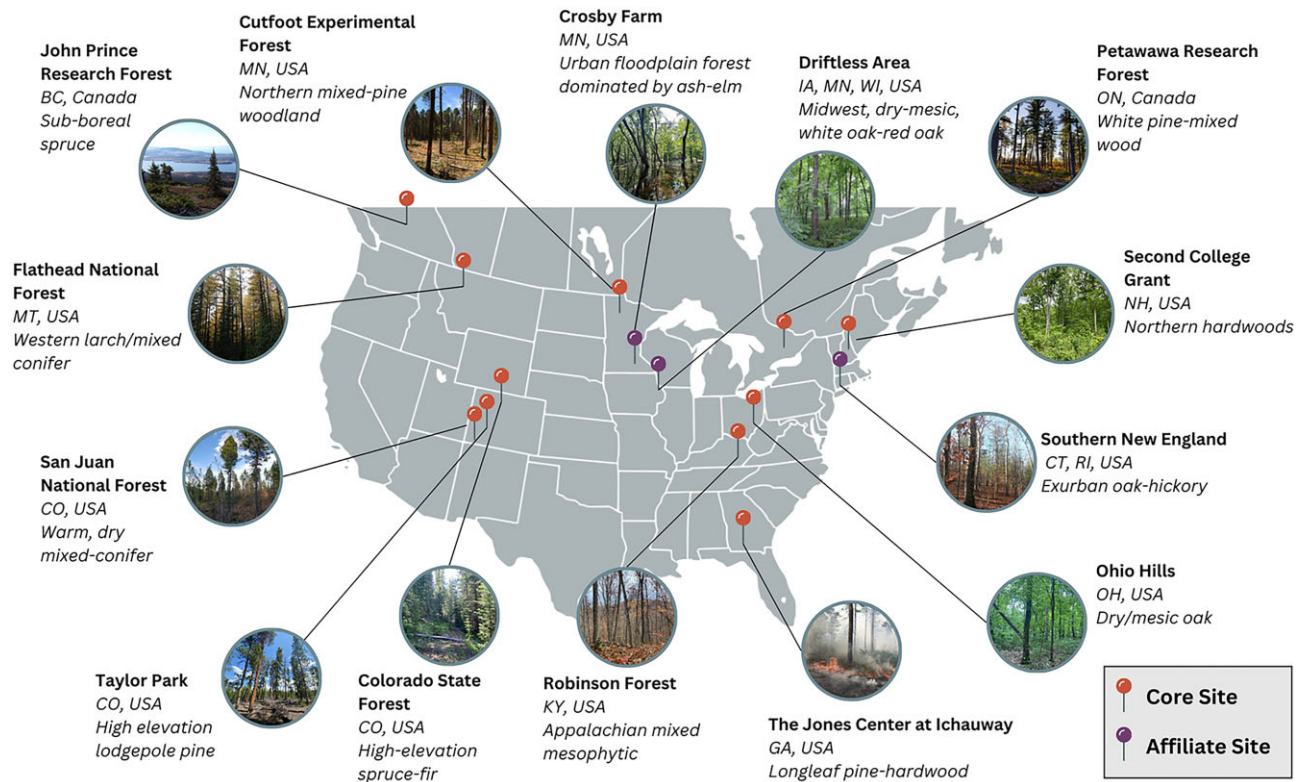


Figure 3. The Adaptive Silviculture for Climate Change (ASCC) Network consists of 14 sites located in diverse forest ecosystem types across the United States and Canada. Affiliate sites meet all network site criteria but are located within fragmented ecosystems or urban settings, do not meet the size criteria of 10 hectares per treatment unit, and some sites are replicated across multiple states.

tailored adaptation actions for each adaptation treatment relative to the reference point. At the initial phase of each experimental trial, a partnership of manager and scientist site leads facilitated by the ASCC Network's leadership team identify a key group of 20–30 partners from local and regional land management organizations and universities who engaged in the facilitated coproduction workshop process. Drawing from the iterative adaptation workshop process (Swanston et al. 2016), the workshop participants discuss and shape the site-specific management goals, ecosystem vulnerabilities, and desired future conditions that map with adaptation concepts specific to their local context, and identify silvicultural tactics or actions to achieve these management goals. Ultimately, these sets of silvicultural tactics are translated into treatments along the resistance, resilience, and transition (and no-action) spectrum.

The ASCC study is designed to maintain key elements that are consistent across all sites within the network while allowing individual sites to tailor treatments to their unique, local contexts (figures 2 and 3, supplemental table S1). All ASCC Network sites use the same experimental approach and study design for treatment types and spatial and temporal factors, allowing sites to evaluate outcomes of adaptation actions over both the short and the long term across the same set of adaptation concepts. Additional design elements consistent across sites in the network include statistically robust replication of the treatments (i.e., four replicates), operational unit sizes (approximately 10 ha per unit), monitoring guidelines for overstory, midstory, and understory vegetation response, and an evaluation window of stewarding and monitoring the ASCC sites 20 years after the implementation. However, the coproduction process also recognizes that success at meeting management goals and objectives in the short versus

long term may look very different across local forest types and that the specific treatments will differ on the basis of local context: forest type, starting conditions and study site layout, local management objectives, climate vulnerabilities and other stressors, social and economic considerations, and the management actions prescribed to meet the adaptation treatments (figure 2; Nagel et al. 2017). Each site also has a unique set of partners with their own set of research and management questions, resulting in unique and individualized monitoring plans for variables that include but are not limited to carbon sequestration potential, fuels reduction, impacts on pollinator habitat, and small mammal herbivory on planted seedlings. See www.adaptivesilviculture.org/experimental-design for details about the experimental design.

A key result of the ASCC experimental framework and workshop process is the coordinated demonstration of multiple, place-based, rigorously applied climate-adaptive silviculture treatments and long-term monitoring. The large-scale field installations also serve as on-the-ground demonstrations, enabling rapid sharing of science and lessons learned with forest managers and partners implementing reforestation and other management strategies for a rapidly changing climate, educators, and a growing profession of providers who deliver widespread hands-on climate change training and consultation.

Emergent trends among ASCC installations and lessons across the network

Each ASCC installation has a unique ecological, socioeconomic, and management context, with the coproduction process gener-

ating distinct desired future conditions and adaptation actions to achieve those conditions. Nevertheless, there are several general themes related to the influence of the primary stressors and vulnerabilities at a site on the associated adaptation strategies applied. For example, the network (figure 3) spans a moisture gradient from semiarid forests in the intermountain United States to humid forests in the northeastern United States. Although an increasing severity and frequency of drought and wildfire is projected across all sites, the management of tree density as an adaptation tactic to reduce risks from drought (cf. Bottero et al. 2017) and wildfire (Davis et al. 2024) are far more widely used at semiarid to dry-mesic sites. Similarly, the prevalence of nonindigenous insects and pathogens is far greater in the eastern portions of North America (Lovett et al. 2016), with ASCC sites in this region frequently including tactics that specifically address these threats, including regeneration harvests to restore and maintain mixed-species conditions and enhance representation of nonhost species (MacLean and Clark 2021).

Another generalizable theme across installations is an emphasis on adaptation tactics that use silvicultural actions to generate increased structural and compositional complexity within the resilience and, in some cases, transition treatments. Resistance treatments, in contrast, generally reflected more uniform application of treatments focused on increasing tree vigor and maintaining current (i.e., starting) compositional conditions. The greater emphasis on heterogeneity in structure and composition for resilience than for the other treatments reflects the recognized importance of ecosystem complexity in generating multiple adaptation and recovery pathways (Puettmann 2014, D'Amato and Palik 2021). Many resilience treatments emphasize multicohort age structures and silvicultural methods that create diverse resource environments, spatially complex distributions of mature trees, and a range of tree size and age classes (Muller et al. 2021, Wikle and D'Amato 2023). In contrast, many transition treatments devote a greater portion of the stand to regeneration of future-adapted tree species, either through creation of large canopy gaps or stand-wide harvests of most mature trees (Crotteau et al. 2019, Wiechmann et al. 2022). Prior to treatment, stands commonly contain some characteristics and components that may contribute to climate resilience, so transition treatments often seek to retain these components even as the treatments substantively change the character of the stand to better align with a range of plausible future climates. Transition treatments may thus include tactics such as retention of mature trees as biological legacies for microsite amelioration, biodiversity benefits, and ecosystem memory (Johnstone et al. 2016). This difference reflects the contrasting goals between resilience and transition options, with the latter emphasizing facilitation of change with a strong focus on species composition including novel mixes, and the former focused primarily on complex stand conditions that may provide options to recover back to identified reference conditions.

A final general theme involves use of forest assisted migration (Pedlar et al. 2012). Forest assisted migration is becoming a common forest adaptation practice with three generally recognized options: assisted population migration (movement of genotypes of a species within its current range), assisted range expansion (movement of species just beyond its current range to future projected suitable habitat), and assisted species migration (longer distance movement of species to new habitats; Williams and Dumroese 2013). Every ASCC site has applied or plans to apply some form of assisted migration, providing valuable operational contexts to understanding the feasibility and outcomes of this emerging practice (Muller et al. 2019, Clark et al. 2022, Thif-

fault et al. 2024). Assisted migration was most frequently applied in transition treatments, with considerations for species selection including future climate suitability, potential functional redundancy with vulnerable species, and susceptibility to known forest health and disturbance issues. The decision-support tools and approaches used to guide how forest assisted migration was applied varied site by site, partially informed by the regional availability of these resources. Localized provenance data and other seed selection tools (McLane and Aitken 2012, Young et al. 2025) were emphasized in some areas, whereas practitioners in other areas relied on tools such as climate-informed seedlot selection tools (Howe et al. 2016, St. Clair et al. 2022), species distribution models such as the Climate Change Tree Atlas (Peters et al. 2020), or regionally defined seed zones (Pike et al. 2020). Importantly, these choices were not made on models alone but codeveloped with community partners and scientists, ensuring that species and genotypes were also selected for their functional traits and alignment with cultural, ecological, and site-specific values. Notably, the value of timber species planted was rarely a priority guiding assisted migration, potentially because of an emphasis on sustaining diverse values and functions through the coproduction process. Ultimately, decisions regarding assisted migration species and genotype selection were constrained by nursery production capacity and the availability of diverse, climate-adapted seedlings (Clark et al. 2023). See figures 4 and 5 for examples of how the gradient of resistance, resilience and transition treatments were applied across two contrasting sites.

Impacts of the ASCC experimental network

In considering the overarching goals of the ASCC network, success can be defined in multiple ways that encompass the practical application of the experimental design that tests adaptation actions, the evaluation of silvicultural treatment success, a coproduction framework that fosters collaborative science–manager partnerships, and the influence of the ASCC Network on advancing effective forest adaptation in research, management, policy, and education. Box 3 summarizes broader application of core ASCC principles as learned from over a decade of experience.

An initial goal of the ASCC project was to establish three to five experimental installations featuring a range of ecosystem types and management approaches. The network has since expanded to 14 networked installations in a variety of forest conditions (figure 3) reflecting the growing demand for applied adaptation science. Moreover, the process of coproduction has enabled the establishment of installations managed by diverse ownerships located on public and private lands in urban, exurban, and rural settings, on USDA National Forest System lands, US and Canadian experimental forests, state forests, university forests, a regional park, and private lands.

The design and implementation of the ASCC Network's experimental framework (box 2, table 1, figures 1 and 2; Nagel et al. 2017) is valuable for manager-driven science for several reasons, each grounded in practicality and clarity. Restoration ecology has long relied on the historical range of variation (often used synonymously with natural range of variation) as a guide for determining what forests should be (Keane et al. 2009). Although historical conditions provide valuable ecological context, strict reliance on them can foster a level of ecological nostalgia that obscures present realities and complicates climate adaptation (Higgs et al. 2014, Jackson 2021, Schuurman et al. 2022). The ASCC Network obviates this debate by using current ecosystem conditions as the baseline for all treatments, thereby grounding experimental com-

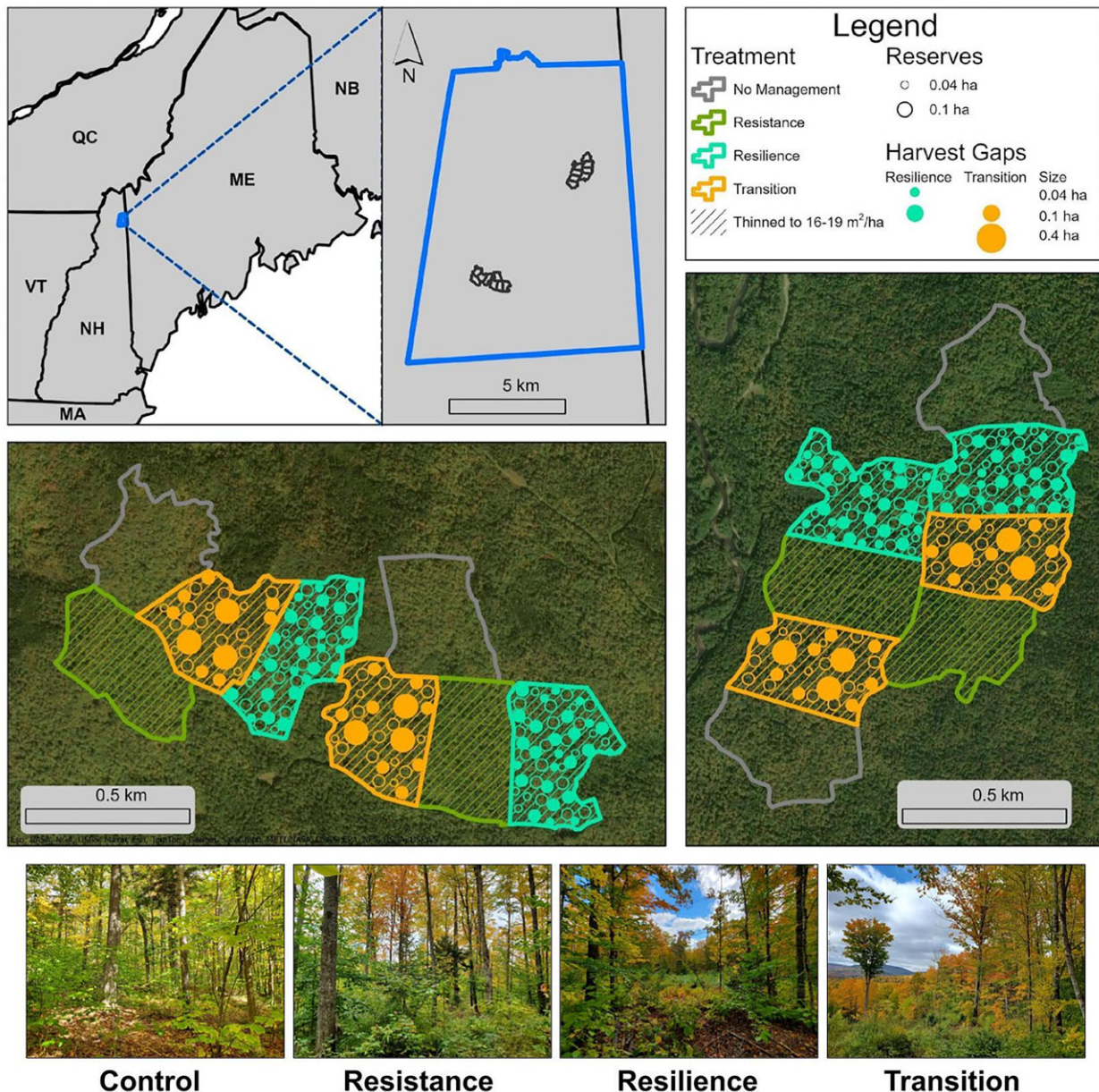


Figure 4. Second College Grant (SCG) ASCC site example. Dartmouth College's SCG consists of approximately 11,000 hectares (ha) of mesic northern hardwood forest, rivers, and wetlands in the Northern Forest region of New Hampshire. The ASCC treatment units at the SCG are blocked into a northern and a southern section, including 200 ha of treatments across the control, resistance, resilience, and transition spectrum. Dominant tree species include sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britton), and American beech (*Fagus americana* Ehrh.), with lesser components of red maple (*Acer rubrum* L.), red spruce (*Picea rubens* Sarg.), and other species. Major climate concerns include wind and ice events, moisture stress, and native and invasive pests and diseases. The SCG resistance treatment includes a single-tree selection, reducing the basal area to 16–18 square meters (m²) per ha, creating a multicohort stand condition that is dominated by sugar maple, favors resistant trees and crown forms to gap-creating disturbance events, and increases the amount of deadwood for carbon sequestration and amelioration of extreme precipitation events. The resilience treatment at the SCG ASCC site includes a hybrid single tree or group selection, where 20% of the treatment unit is within 0.04–0.10 ha gaps, 20% of the unit is within reserves, and the remaining matrix is thinned to 16–18 m² per ha. The resilience treatment also emphasizes increasing the proportion of yellow birch, spruce, and red maple. The multiple combinations of species composition and structure present allows for multiple pathways to recovery from disturbance. Finally, the transition treatment at the SCG ASCC site includes a continuous cover irregular shelterwood, where 20% of the treatment unit is within 0.10–0.40 ha gaps, 10%–20% of the treatment unit is within reserves, and the remaining matrix is thinned to a basal area of 16–18 m² per ha. The transition treatment also includes planting future-adapted species (northern red oak, *Quercus rubra* L.; bitternut hickory, *Carya cordiformis* (Wangenh.) K. Koch; eastern white pine, *Pinus strobus* L.; eastern hemlock, *Tsuga canadensis* (L.) Carr.; basswood, *Tilia americana* L.; black birch, *Betula lenta* L.; bigtooth aspen, *Populus grandidentata* Michx.; and chestnut, *Castanea dentata* (Marsh.) Borkh.) in a subset of the 0.10–0.40 ha gaps. Source: Figure created by Jennifer Santoro.

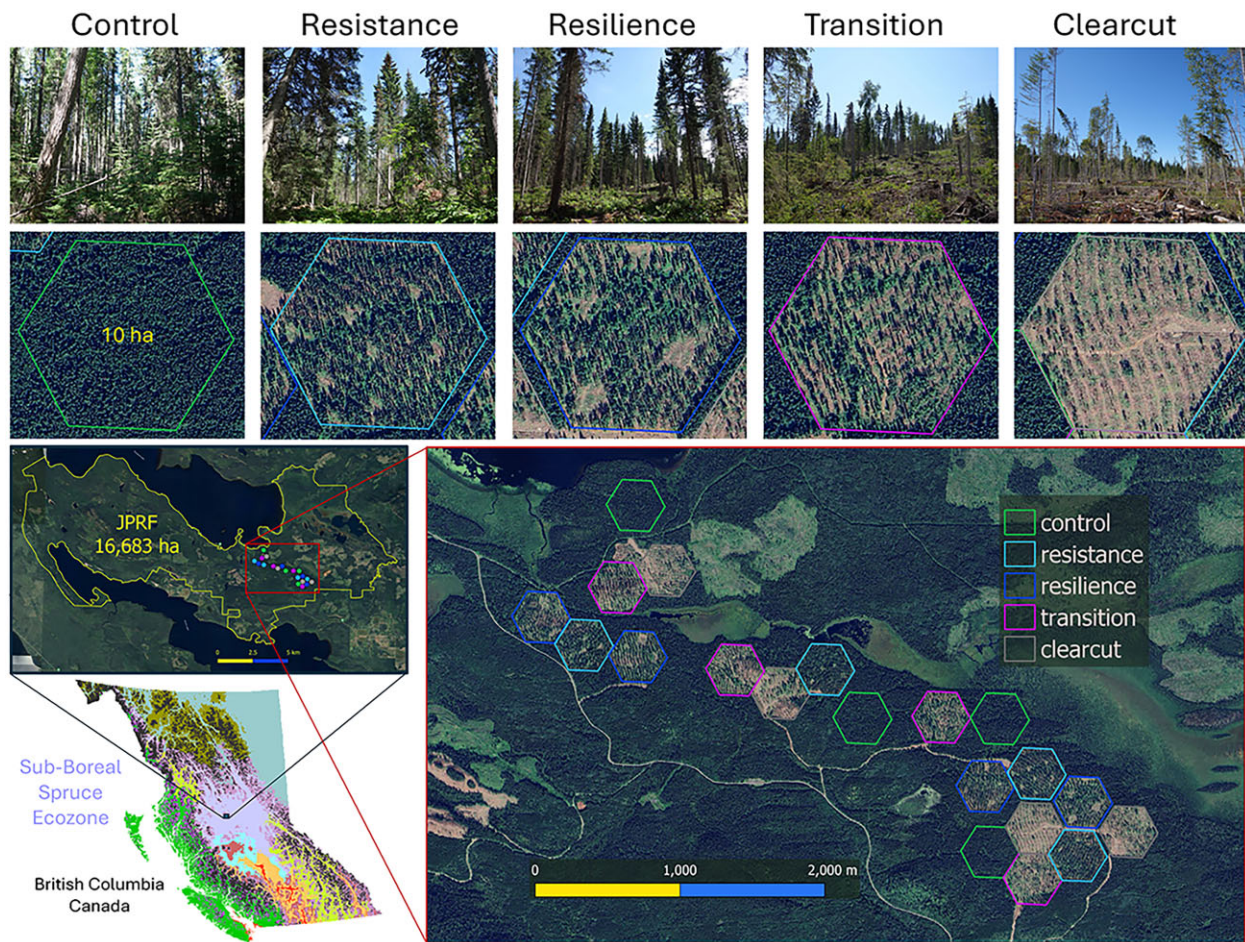


Figure 5. John Prince Research Forest (JPRF) ASCC site example. The JPRF is a 16,683-hectare (ha) research forest located in the subboreal spruce biogeoclimatic zone in northern British Columbia, Canada, and jointly managed by the Tl'azt'en and Binche Whut'en First Nations and the University of Northern British Columbia. The ASCC site at the JPRF is 200 ha in size, with 16 hexagonal units (10 ha each) representing the control, resistance, resilience, and transition treatments. There are also four additional 10-ha hexagon units representing the common regional practice of clearcutting with reserves, which is one of the three general categories of silvicultural systems used in British Columbia (clearcutting, partial cutting, and clearcutting with reserves). Climate projections for the subboreal spruce zone could include either a warmer and drier future condition similar to interior Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests, or a warmer and wetter future condition similar to interior cedar-hemlock forests. The resistance treatment at the JPRF ASCC site includes a modified or hybrid group selection system, retaining approximately 15 square meters (m^2) per ha of basal area, reducing the amount of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and promoting Douglas fir, spruce (*Picea glauca* (Moench) Voss, *Picea engelmannii* Parry), and deciduous species. The resilience treatment includes a variable retention harvest, retaining 10–12 m^2 per ha basal area, thinning from above to increase vigor, removing ladder fuels, and shifting the overstory composition. The resilience treatment also includes planting locally sourced Douglas fir, as well as Douglas fir, hybrid white spruce, and pine from southern seed zones, and natural regeneration of aspen is promoted in the openings. Finally, the transition treatment at the JPRF ASCC site includes a shelterwood system with a lower residual basal area of approximately 5–8 m^2 per ha with a focus on maintaining current species diversity while also encouraging a strong push to future climate-adapted species. Species planted in the transition treatment include species currently found on the forest (Douglas fir; lodgepole pine, *Pinus contorta* var. *latifolia* Engelm. Dougl. ex Loud.; birch, *Betula papyrifera* Marsh.; aspen (*Populus tremuloides* Michx.) and novel species to the forest (western red cedar, *Thuja plicata* Donn ex D. Don; western hemlock, *Tsuga heterophylla* (Raf.) Sarg.; ponderosa pine, *Pinus ponderosa* Dougl. Ex P. and C. Laws.; and western larch, *Larix occidentalis* (Nutt.) Nees). Source: Figure created by Che Elkin.

parisons of resistance, resilience, and transition strategies in existing forests rather than in idealized past states. Although managers may have different views (McGann et al. 2023) on the appropriateness of the starting condition and treatments based on their values and land management objectives, this approach provides an objective and concrete basis for grounding the discussion about adaptation options and evaluation of treatment effects.

The experimental framework uses the resistance–resilience–transition conceptual framework (table 1, figure 1) to describe the intent and direction of adaptation relative to the starting condition, which is helpful in describing the value and effectiveness of those actions in working toward certain outcomes. At the same time, the framework recognizes that each location represents a

different starting point (i.e., biologically and ecologically, forest health stressors and vulnerabilities, management regimes), so each set of adaptation treatments will always be dependent on the local management context. This reveals differences in local values, ecosystems, and approaches to forest management, while creating clarity around localized examples of climate adaptation that clearly meet management intent and outcomes.

The experimental framework implements a full range of management options and interventions, understanding that not all treatments are equally practicable in all locations. It is anticipated that some treatments may fail at some point in the future; however, treatments cannot begin at the point of failure. For instance, in areas already experiencing significant impacts

Box 3. Broader application of ASCC principles.

The ASCC Network is built on the foundation of the Climate Change Response Framework, which was created to accelerate the shift from academic principles and definitions of adaptation to practical, coproduced, science-based practices used in on-the-ground forest management. The ASCC approach reverses the original focus of the framework by executing adaptation practices within a robust experimental network to test, inform, refine, and challenge academic principles and definitions. ASCC builds off a tradition in ecology whereby networks of sites leverage like-experimental designs to examine broad ecological processes and phenomena (e.g., <https://lternet.edu>). Intentional science coproduction has allowed ASCC to have success in short order and with few resources (i.e., no large grant or funding program). Building from this, there are now emerging examples in the coproduction space inspired by ASCC that use this model (e.g., <https://diverseproject.uqo.ca>).

In the present box, we distill the core principles from over a decade of experience in conceiving, establishing, and maintaining the ASCC experimental framework. These principles may be applied to other experimental settings, with an emphasis on tailoring frameworks to local ecological, cultural, and resource management contexts while maintaining core experimental integrity and climate adaptation relevance.

Coproduce science with local managers, scientists, and community partners to leverage place-based knowledge

Engage local and regional forest managers, scientists, Indigenous knowledge holders, and policymakers in early planning stages to ensure experimental relevance to local ecosystems, ownerships, vulnerabilities, traditions, and management practices. Empowering local stewards to lead sites also allows for more nimble decision making, monitoring and adaptation, effective science delivery to local management communities, and robust funding opportunities over time.

Use the resistance–resilience–transition gradient to communicate and assess how adaptation actions vary in their effects on forests

Resistance–resilience–transition is a flexible framework used to clarify action and intent, that can be applied within various ecosystems and regions, globally. Site partners consider and define each adaptation concept in the context of baseline conditions, then localize management approaches suited to regional contexts.

Ensure that treatments are feasible and representative of operational scales

Experiments are most effective when they match the scale and practical constraints of real-world regional forest management practices, ensuring results are both realistic and actionable within typical economic and operational limits.

Determine baselines and establish benchmarks for change

Prior to treatment, establishing a clear understanding of site-level baselines and identifying potential thresholds for change is foundational to all future analyses, decisions, and even basic communication. The conditions present at the initiation of the project are used as the environmental baseline for establishing the experimental reference point. In the ideal situation the baseline and reference are identical, but in some highly degraded systems resistance actions may already be considered nonviable. In these cases, a viable, defensible reference point that deviates as little as possible from the baseline may need to be created alongside adaptation strategies. This process does not necessarily aim to restore previous states, which may be precluded by environmental change or otherwise involve significant ecosystem transition.

Use desired future conditions as thresholds for success

Desired future conditions provide tangible benchmarks for forest character and function over time, including explicit targets for characteristics such as species and genetic composition, structure, function, and ecosystem services. Articulating these early on help guide treatment development and other key decisions as well as ensure that all partners share a common vision for the forest's future. Clear short- and long-term desired future conditions are a place-based approach for defining what "success" means in the context of resilience theory.

Incorporate climate novelty and test extreme scenarios

In addition to testing more conservative management scenarios, the experimental nature of this work encourages actions that move beyond historic practices in designing treatments that test responses to more novel or extreme futures. This is especially true in the transition treatment, where managed transition of ecosystem structure (e.g., closed canopy to woodland), inclusion of nonpresent future-adapted species or genotypes, or changes in traditional use (e.g., timber, recreation) would otherwise challenge contemporary views of conservation.

Plan for flexible management and communication to build capacity and foster knowledge exchange

Build in processes and mechanisms for iterative adjustments in management and ensure findings are communicated effectively to both scientific and practitioner audiences. Support training, colearning, and collaborative analysis across sites and institutions, especially in underresourced regions.

from global change such that forest conditions are already considered untenable or highly degraded, a resistance approach may essentially begin at the point of failure, rendering actions that keep it as it is nonviable. Stronger intervention may be necessary in these stands to establish a defensible reference point, although far short of what would normally be considered as restoration. As another example, ASCC reliance on coproduction ensures that treatments are grounded in approaches that practitioners

can realistically implement given their regulatory or social context, sometimes resulting in an unwillingness to implement certain higher-intensity harvest treatments associated with transition treatments (e.g., clearcuts) in areas with smaller administrative units. Conversely, tree planting is commonplace in more developed urban and exurban areas, so the application of forest-assisted migration for transition may be viewed more favorably and applied more readily. The intentional design of the ASCC experi-

mental framework supports active exploration of the degree of intervention that is required to achieve a range of desired outcomes. Furthermore, the experimental framework provides a consistent method to evaluate adaptation outcomes, enables quality control of the development process, ensures consistent adherence to the framework with the creation of each site, and facilitates the opportunity for network-wide research questions and comparisons. Importantly, the explicit articulation of desired future conditions for each treatment is not only crucial to evaluating adaptation outcomes, but also to clearly communicating and socializing the need for actions before and after implementation.

Success may also be defined by the climate-adaptive silvicultural treatment that best meets the identified desired future condition of the associated treatment (i.e., where the adaptation target was met and the intended management goals were achieved). Forests are long-lived, therefore the effects of forest management may be realized at long timescales that vary with the ecology of a given ecosystem. At the same time, the ASCC installations are still in the early stages of implementation and more time will be needed to yield additional information regarding the long-term effectiveness of the resistance–resilience–transition treatments. Nonetheless, analysis of early results are already yielding insights for the scientific and practitioner communities regarding treatment success and are being used to inform the next round of treatments within the ASCC sites, as well as management practices implemented by the surrounding communities (see “Emergent trends among ASCC installations and lessons across the network” section above). ASCC installations are also providing insights into the application of forest assisted migration across the adaptation spectrum, which is facilitating development of early guidance on assisted migration strategies for several forest types (Palik et al. 2022) and also directly informing organizational planning and integration of forest assisted migration into reforestation efforts (e.g., USFS led Forestry Assisted Migration Technical Assistance Team, Superior National Forest Assisted Migration Plan; Frerker et al. 2023). Furthermore, the experimental framework is designed to directly improve understanding and has generated insights into the influence of climate-adaptive management on key ecosystem processes (e.g., Jevon et al. 2019, Green et al. 2022, Read et al. 2023) and components of biodiversity (e.g., Stephens et al. 2021, Borgman-Winter et al. 2022). These successes collectively serve to advance and iterate how adaptation can and is being applied to reduce uncertainty and achieve desirable future outcomes.

The ASCC Network is providing important contributions to the growing body of work regarding how society responds and adapts to immense change in forests and other ecosystems. ASCC sites provide a canvas that is attracting additional scientists from a diversity of disciplines to further understand ecosystem processes and help inform climate-adaptive approaches that consider a range of taxa, desired outcomes, and values. To date, since the initial publication of Nagel and colleagues (2017), the ASCC experiment has generated at least 26 peer-reviewed manuscripts among a diverse array of topics, which are cited by over 300 unique peer-reviewed articles (data obtained from Clarivate Analytics, Web of Science 2025). Cited materials are predominantly related to disciplines in forestry (50%) and ecology (15%) but also include numerous examples from transdisciplinary research including aquatic and rangeland management, materials science, and entomology and zoology. This, combined with informing other subsequent climate adaptation frameworks (i.e., resist–accept–direct; cf. Schurman et al. 2022), underscores the value of large-scale ecological networks such as ASCC and the incorporation of adaptation

frameworks such as resistance–resilience–transition for the evaluation of resource management from the scientific community.

This grassroots effort was driven by a coproduction process that created collaborative science–management partnerships, which has developed to include over 200 primary collaborators across the network of sites, resulting in actionable science that directly addresses complex and novel challenges related to climate change. The processes used to establish and maintain sites illustrate many of the best practices that have been identified for science coproduction (see box 3; Beier et al. 2016, Enquist et al. 2017). Of particular note is the continuous engagement of multidisciplinary researchers working with local managers to facilitate long-term dialogue throughout creation, implementation, and monitoring of climate-adaptive silviculture treatments, as well as effective communication of the results with the broader community. The designated lead scientist and lead land manager are collectively responsible for ensuring the relevance of place-based research questions and supporting localized partnerships. This manager–scientist partnership is also key to overcoming the challenges associated with successfully applying adaptation concepts on the ground, where constraints such as varying slope, aspect, topography, contractor capacity, nursery availability, and community scoping processes, must all be navigated prior to implementation. After the science and management leads have navigated the challenges of implementation and monitoring efforts are underway, they continue to contribute to biannual network-wide meetings that are focused on creating and developing a broad community of practice that supports climate adaptation activities across the science–management spectrum and ensures adaptability of the work in the long term.

As the network has developed, engagement has expanded to include a broader array of partners. For example, three of the installations are located within fragmented forest landscapes and higher human populations (Crosby Farm, Driftless, and Southern New England); although these sites have smaller treatment areas reflecting the constraints on local forest systems, they have rich collaborations that include nonprofit conservation organizations, municipalities, and local Indigenous communities. Over time, the network has also grown in its ability to engage with Native American tribes and First Nations, including strong collaborations with the Leech Lake Band of Ojibwe at the Cutfoot Experimental Forest and collaborative management among the Tl’azt’en First Nation, Binche Whut’en, and the University of Northern British Columbia at the John Prince Research Forest.

Beyond the experimental network, its silvicultural treatments, and its local community of practice, the ASCC Network is informing broader integration of climate adaptation in many different arenas. Land management professionals, students, and the public are exposed to climate adaptation science and application in real world, operational settings through intentional science delivery, training, and research mentorship of students and postdoctoral fellows. Network collaborators provide presentations, field tours, and trainings that directly reach thousands of people each year, in addition to broader media exposure. As one example, over 500 forestry and natural resource professionals (primarily federal with some state and tribal) have been trained using the ASCC site examples and resistance–resilience–transition framework through the USDA Forest Service’s National Advanced Silviculture Program. The earliest climate adaptation curricula in the program (circa 2007–2008) entailed presentation of basic climate science and exposure to adaptation concepts (Nagel et al. 2010); today’s curriculum involves a facilitated session where

participants develop a spectrum of adaptation treatments along the resistance–resilience–transition gradient for specific contexts, and field trips to ASCC installations where regionally available. Furthermore, ASCC concepts and findings are actively being integrated into at least 10 collegiate forestry curricula across the United States from associates to graduate programs.

Conclusions

As this effort continues to generate scientific results, the power and utility of the ASCC Network to show how adaptation works is expected to increase through collaborative and adaptive practice, providing increasingly valuable insights over time of how to implement climate change adaptation to meet diverse needs. In the present article, we describe the experimental and coproduction framework used to build a robust, replicated network of experimental sites testing a common climate-adaptive forest management framework in a real-world context. Although the network remains in the early stages of development (relative to the long timescales of forests and the impacts of climate change), this work serves as a model framework for coproduction of adaptation science applicable to forests and other contexts and ecosystems managing for uncertainty.

Supplemental material

Supplemental data are available at BIOSCI online.

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