Lessons Learned from Climate Adaptation Projects in Northern Hardwood Forests

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Climate change will present challenges for northern hardwood forests through the coming century. Many land managers are seeking information and resources to inform forest management activities given a wide range of potential future conditions. The field of climate adaptation is growing rapidly, with increased information available regarding the vulnerability of forests to climate change, tools for considering climate change in management planning and decision making, and management options to support adaptation to future conditions.

Climate change vulnerability assessments for the midwest and northeast United States indicate that forest vulnerability varies regionally due to differences in projected future climate, species range changes, and nonclimate stressors. Many northern hardwood tree species are expected to lose suitable habitat at the southern extent of their species range and in locations where climate change exceeds biological thresholds (Peters 2020, Prasad et al. 2020). For instance, central Appalachian northern hardwood forests are rated as highly vulnerable because warmer and drier climate conditions and enhanced disturbance are expected to increase stress on several dominant species that are at the southern extent of their range in this region (Butler et al. 2015). Northern hardwood forests in the mid-Atlantic region have moderate-high vulnerability, largely due to interactions among climate change and other stressors present in this highly populated and heavily fragmented landscape (Butler-Leopold et al. 2018). In comparison, northern hardwood forests in the Upper Great Lakes and Northeast are rated as having low-moderate levels of vulnerability given the expectation that regional forests and tree species have a greater capacity to cope with climate change impacts in the absence of major disturbance (Handler et al. 2014a, Handler et al. 2014b, Janowiak et al. 2018, Janowiak et al. 2014).

Two complementary adaptation efforts support natural resource professionals integrating climate change information into management by providing decision-support tools, technical assistance, and real-world demonstrations. The Climate Change Response Framework (CCRF; www.forestadaptation.org) is a collaborative, cross-boundary approach among scientists, managers, and landowners to incorporate climate change considerations into natural resource management. In addition to the aforementioned assessments, CCRF tools and resources include an Adaptation Workbook, multiple menus of adaptation strategies, and a network of more than 500 adaptation

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demonstrations featuring real-world management projects that have used the Adaptation Workbook and menus (Swanston et al. 2016). The Adaptive Silviculture for Climate Change (ASCC; www.adaptivesilviculture.org) network of experimental trials provides robust silvicultural experiments to test adaptation options for resistance, resilience, and transition in various forest types in the United States and Canada (Nagel et al. 2017). Together, projects implemented through CCRF and ASCC serve as critical examples of forest adaptation, and evaluation of these projects can inform adaptive management in northern hardwood forests and other ecosystem types.

Adaptation projects in northern hardwood forests vary widely based on numerous local factors, such as landowner goals, site and soil conditions, legacies of past management, forest species composition and age structure, climate change impacts, and nonclimate stressors. Simultaneously, adaptation projects in northern hardwoods often share similar characteristics based on a manager's aim to resist climate change, increase ecosystem resilience, or facilitate transitions toward new forest assemblages (Table 1). ASCC study treatments in northern New Hampshire, described below, illustrate the trend seen across many adaptation projects in northern hardwood forests where the modification of gap sizes and harvest levels are used to mimic natural disturbance and create light conditions to facilitate regeneration of desired species: shade tolerant mesic species in resistance; mid-tolerant, future-adapted, native species in resilience; and future-adapted, mid- and intolerant species in transition.

Adaptation projects are fundamentally experimental given that controls for a no-climate-change situation do not exist, making monitoring and evaluation of these projects critical for adaptive management. ASCC trials provide an opportunity to evaluate the effectiveness of adaptation treatments in an experimental framework. Additionally, the use of climate-informed inventory has been used at adaptation demonstration sites like Caroline Lake Preserve in northern Wisconsin to inform management decisions and evaluate outcomes (Janowiak et al. 2017).

ADAPTIVE SILVICULTURE IN NORTHERN HARDWOODS

The ASCC northern hardwoods project takes place at the Dartmouth Second College Grant (SCG), an unincorporated township of 10,800 ha in northern New Hampshire owned and managed by Dartmouth College. In the 160-ha research area, elevations vary from 484 to 650 meters. Mean annual temperature ranges from -12 °C (January) to 17 °C (July) and annual precipitation is 117.1 cm (NOAA 2020). Soils are coarse loamy glacially derived tills (Jevon et al. 2019, NRCS 2020). The research site is a northern hardwood forest, dominated by sugar maple and significant components of yellow birch and beech. The adaptation treatments were codeveloped with a group of scientists and managers over a multi-day workshop within the resistance, resilience, and transition framework (Table 1) and were implemented in 2017.

FOREST COMPOSITIONAL CHANGE

Central to the development of the adaptation treatments are concepts of structural, functional, and compositional diversity that increase adaptive capacity. Forests containing a diversity of species and functional traits are more likely to have some species or traits that can persist through novel disturbance and species-diverse temperate forests have shown greater resistance to drought than less diverse forests (Jactel et al. 2017). A diversity of species, age, and size classes may confer some protection from wind events, as well as insect and fungal pests (Foster 1988, Gerlach et al. 2011, Jactel and Brockerhoff 2007). Further, diverse stands have numerous pathways to withstand and recover from novel disturbance (Fahey et al. 2018, Messier et al. 2014). Varying levels of connectivity between different structural and compositional elements also contribute to adaptive capacity and understanding the arrangement of elements is an important component of

Table 1.—Selected climate change impacts and adaptation options in northern hardwood forests

Factor	Description		
Forest type	Northern Hardwoods		
Climate change impacts	• Higher temperatures and altered precipitation can increase heat stress, moisture stress, and drought risk in this mesic forest type. • Heavy precipitation events increase risk of overland flows and erosion on slopes, and flooding in low-lying areas • Shifts in tree species distributions in response to changing conditions. • Increases in insect pests and pathogens as agents move northward or respond to other changes in weather and climate • Interactions with other stressors, such as deer browse, invasive earthworms, and invasive plants • Altered disturbance regimes, including potential for increased damage from extreme storms and wind		
Adaptation options	Resistance	Resilience	Transition
Definition (Millar et al. 2007, 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.
Goal (Nagel et al. 2017)	Maintain relatively unchanged conditions over time.	Allow some change in current conditions, but encourage an eventual return to reference conditions.	Actively facilitate change to encourage adaptive responses.
Example management actions based on CCRF adaptation demonstrations	Thinning, single-tree, or small-group selection to maintain current shade-tolerant species composition. Control of competing vegetation or animal browse to support native plant community.	Small-group selection or small-patch harvests to increase native mid-tolerant associate species such as yellow birch Natural regeneration or planting to increase representation of locallyassociated species, such as red oak or white pine. Control of competing vegetation or animal browse to support native plant community.	Irregular shelterwood, large gap/patch cuts, or other harvests to alter composition toward future-adapted species. Natural regeneration of future-adapted species with a local seed source. Planting of future-adapted species, including assisted migration species. Control of competing vegetation or animal browse to support development of future-adapted assemblage.
ASCC treatment objectives for Second College Grant site	Single tree selection using Arbogast guidelines maintaining current forest composition: sugar maple > beech > yellow birch > red maple > red spruce > other Select for healthy and resistant individuals within current structure Maintain a continuous, multi-layered canopy Initiate a new cohort that reflects current overstory species composition Maintain current abundance of snags and downed dead wood (~1 snag/ac, 280 ft^3/ac downed dead wood)	Group selection with gaps and reserves 0.1–0.25 acres Thinned matrix Sugar maple ≤ 30–40% of species composition, yellow birch, beech, red maple, red spruce, and other species together comprise 60–70% of stand composition Multiple combinations of species composition and structure present (multiple pathways to recovery from disturbance) Multiple age classes present (uneven-aged, ~5 cohorts) Increased amount of dead wood (snags: 1–3/acre; downed dead: >300 ft^3/acre)	Continuous cover irregular shelterwood with gaps and reserves 0.25–1 acre Thinned matrix Dominance of future-adapted species currently onsite: yellow birch, red maple, beech Planted offsite climate-adapted species Change species composition while also increasing species richness (portfolio approach): 50% regeneration is future-adapted species already on site (n. hardwoods), 50% new species from off-site (slightly shifting away from strictly northern hardwoods) Uneven-aged, 20% of the area in regeneration (gaps) Create irregular vertical and horizontal structure, uneven-sized forest ecosystem, 50% canopy cover (50–60 ft^2/acre BA) across stand on average, 70–80 ft^2/acre BA in matrix

understanding the adaptive capacity conferred by adaptation treatments (D'Amato and Palik 2021, Messier et al. 2019). Analyses of forest structure and composition help quantify adaptive capacity for each treatment.

Four years after harvest, canopy tree species composition remains similar across the three treatments and control stands, indicating the challenge of attempting to shift species composition in a forest dominated by a small number of species using uneven-aged management techniques. Composition of regeneration shows more difference among treatments and reflects treatment goals of changing species dominance. The control stands and resistance treatment both show natural regeneration with the same composition as the overstory—sugar maple dominant, with considerable proportions of yellow birch and beech. Canopy gaps drive regeneration composition in the resilience and transition treatments. In these treatments, yellow birch and red maple seedlings are more abundant, and early successional species such as pin cherry and aspen also contribute notably to species diversity.[2] These patterns indicate that individual treatment components, such as gaps and reserves, will influence adaptive responses in different ways. Given that the silvicultural treatments have a limited ability to alter canopy tree composition, regeneration will likely drive changes in species composition, although changes will take a long time to become apparent in the canopy.

ADAPTATION PLANTINGS FOR TRANSITION

The pace of climate change exceeds that of historic tree migration, leading to the potential misalignment of species with future climate conditions (Janowiak et al. 2018, Sittaro et al. 2017, Zhu et al. 2012). The planting of species projected to be future climate-adapted (FCA) is an adaptive strategy that can support forest transition to new compositions (Pedlar et al. 2012, Williams and Dumroese 2013). Adaptation plantings may serve as critical sources for future populations, via population enrichment (augmentation of the pool of species onsite that may be FCA) or assisted range expansion (assisted migration of FCA species not onsite from adjacent climate zones). To test this, the SCG transition treatment included adaptation plantings of nine species (n = 4,675 seedlings) (Table 1). Species were selected using species distribution models (Janowiak et al. 2018, Peters 2020) and localized using regional manager and scientist knowledge with emphasis placed on species with similar functional traits relative to species on site forecasted to decline.

Over three growing seasons, 2,609 transplants survived (55.8 percent). Seedling growth and survival varied considerably across species. The primary biophysical drivers controlling seedling performance (survival/growth) were vegetative competition (-/-), seedling functional attributes (+/+), initial seedling size (+/-), and transfer distance inferred by population enrichment versus assisted range expansion (-/-). Vegetative competition played an important role with sites containing well developed natural regeneration more resistant to the introduction of adaptation plantings; however, heavily browsed sites diminished the strength of local vegetative competition and likely favored planted species that were less palatable. Notably, population enrichment species performed significantly better than assisted range expansion species, which exhibited more maladaptation (e.g., dieback, winter injury, reduced growth and survival), further highlighting the challenges of assisted migration.

Managers considering adaptation plantings may face additional challenges, namely extreme climate events (Park and Talbot 2018) and limited nursery capacity and infrastructure (Fargione

[2] Scientific names of tree species listed: yellow birch (*Betula alleghaniensis*); red maple (*Acer rubrum*); pin cherry (*Prunus pensylvanica*); aspen (*Populus* spp.); sugar maple (*Acer saccharum*).

et al. 2021). For example, the SCG planting trials experienced an extreme drought during planting and multiple late spring frost events with negative consequences on seedling performance that differed by species. Furthermore, securing a diverse suite of species and functional traits proved to be an additional hurdle because few regional nurseries offered FCA species that support a range of ecosystem services. In summary, although silvicultural responses to shifts in future species habitats may include adaptation plantings to facilitate FCA species establishment, the strength of local site competition and herbivory, functional traits, adaptation planting type, extreme climate, and the availability of quality and diverse nursery stock will be important for determining the efficacy of efforts to transition forest composition.

LITERATURE CITED

Butler-Leopold, P.R.; Iverson, L.R.; Thompson, F.R., III; Brandt, L.A.; Handler, S.D. [et al.]. 2018. **Mid-Atlantic forest ecosystem vulnerability assessment and synthesis: a report from the Mid-Atlantic Climate Change Response Framework project.** Gen. Tech. Rep. NRS-181. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 294 p. https://doi.org/10.2737/NRS-GTR-181.

Butler, P.R.; Iverson, L.; Thompson, F.R., III; Brandt, L.; Handler, S. [et al.]. 2015. **Central Appalachians forest ecosystem vulnerability assessment and synthesis: a report from the Central Appalachians Climate Change Response Framework project.** Gen. Tech. Rep. NRS-146. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 310 p. https://doi.org/10.2737/NRS-GTR-146.

D'Amato, A.W.; Palik, B.J. 2021. **Building on the last "new" thing: exploring the compatibility of ecological and adaptation silviculture.** Canadian Journal of Forest Research. 51(2): 172–180. https://doi.org/10.1139/cjfr-2020-0306.

Fahey, R.T.; Alveshere, B.C.; Burton, J.I.; D'Amato, A.W.; Dickinson, Y.L. [et al.]. 2018. **Shifting conceptions of complexity in forest management and silviculture.** Forest Ecology and Management. 421: 59–71. https://doi.org/10.1016/j.foreco.2018.01.011.

Fargione, J.; Haase, D.L.; Burney, O.T.; Kildisheva, O.A.; Edge, G. [et al.]. 2021. **Challenges to the reforestation pipeline in the United States.** Frontiers in Forests and Global Change. 4: 8. https://doi.org/10.3389/ffgc.2021.629198.

Foster, D.R. 1988. **Species and stand response to catastrophic wind in central New England, U.S.A.** Journal of Ecology. 76(1): 135–151. https://doi.org/10.2307/2260458.

Gerlach, J.P.; Reich, P.B.; Puettmann, K.; Baker, T. 2011. **Species, diversity, and density affect tree seedling mortality from Armillaria root rot.** Canadian Journal of Forest Research. 27: 1509–1512. https://doi.org/10.1139/x97-098.

Handler, S.; Duveneck, M.J.; Iverson, L.; Peters, E.; Scheller, R.M. [et al.]. 2014a. **Michigan forest ecosystem vulnerability assessment and synthesis: a report from the northwoods Climate Change Response Framework project.** Gen. Tech. Rep. NRS-129. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 229 p. https://doi.org/10.2737/NRS-GTR-129.

Handler, S.; Duveneck, M.J.; Iverson, L.; Peters, E.; Scheller, R.M. [et al.]. 2014b. **Minnesota forest ecosystem vulnerability assessment and synthesis: a report from the northwoods Climate Change Response Framework project.** Gen. Tech. Rep. NRS-133. Newtown Square, PA; U.S.

Department of Agriculture, Forest Service, Northern Research Station. 228 p. https://doi.org/10.2737/NRS-GTR-133.

Jactel, H.; Bauhus, J.; Boberg, J.; Bonal, D.; Castagneyrol, B. [et al.] 2017. **Tree diversity drives forest stand resistance to natural disturbances.** Current Forestry Reports. 3(3): 223–243. https://doi.org/10.1007/s40725-017-0064-1.

Jactel, H.; Brockerhoff, E.G. 2007. **Tree diversity reduces herbivory by forest insects.** Ecology Letters. 10(9): 835–848. https://doi.org/10.1111/j.1461-0248.2007.01073.x.

Janowiak, M.K.; D'Amato, A.W.; Swanston, C.W.; Iverson, L.; Thompson, F.R., III [et al.]. 2018. **New England and northern New York forest ecosystem vulnerability assessment and synthesis: a report from the New England Climate Change Response Framework project.** Gen. Tech. Rep. NRS-173. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 234 p. https://doi.org/10.2737/NRS-GTR-173.

Janowiak, M.K.; Iverson, L.R.; Mladenoff, D.J.; Peters, E.; Wythers, K.R. [et al.]. 2014. **Forest ecosystem vulnerability assessment and synthesis for northern Wisconsin and western Upper Michigan: a report from the Northwoods Climate Change Response Framework project.** Gen. Tech. Rep. NRS-136. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 247 p. https://doi.org/10.2737/NRS-GTR-136.

Janowiak, M.K.; Iverson, L.R.; Fosgitt, J.; Handler, S.D.; Dallman, M. [et al.]. 2017. **Assessing stand-level climate change risk using forest inventory data and species distribution models.** Journal of Forestry. 115(3): 222–229. https://doi.org/10.5849/jof.2016-023R1.

Jevon, F.V.; D'Amato, A.W.; Woodall, C.W.; Evans, K.; Ayres, M.P. [et al.]. 2019. **Tree basal area and conifer abundance predict soil carbon stocks and concentrations in an actively managed forest of northern New Hampshire, USA.** Forest Ecology and Management. 451: 117534. https://doi.org/10.1016/j.foreco.2019.117534.

Messier, C.; Bauhus, J.; Doyon, F.; Maure, F.; Sousa-Silva, R. [et al.]. 2019. **The functional complex network approach to foster forest resilience to global changes.** Forest Ecosystems. 6(1): 21. https://doi.org/10.1186/s40663-019-0166-2.

Messier, C.; Puettmann, K.J.; Coates, K.D. 2014. **Managing forests as complex adaptive systems: building resilience to the challenge of global change.** New York, NY: Earthscan from Routledge. 368 p.

Millar, C.I.; Stephenson, N.L.; Stephens, S.L. 2007. **Climate change and forests of the future: managing in the face of uncertainty.** Ecological Applications. 17(8): 2145–2151. https://doi.org/10.1890/06-1715.1.

Nagel, L.M.; Palik, B.J.; Battaglia, M.A.; D'Amato, A.W.; Guldin, J.M. [et al.]. 2017. **Adaptive silviculture for climate change: a national experiment in manager-scientist partnerships to apply an adaptation framework.** Journal of Forestry. 115(3): 167–178. https://doi.org/10.5849/jof.16-039.

NOAA. 2020. **NOWData - NOAA online weather data.** Chapel Hill, NC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Southeast Regional Climate Center. https://www.weather.gov/climateservices/nowdatafaq (accessed February 26, 2020).

NRCS. 2020. **Web soil survey.** U.S. Department of Agriculture, Natural Resource Conservation Service. https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm (accessed March 16, 2020).

Park, A.; Talbot, C. 2018. **Information underload: ecological complexity, incomplete knowledge, and data deficits create challenges for the assisted migration of forest trees.** BioScience. 68(4): 251–263. https://doi.org/10.1093/biosci/biy001.

Pedlar, J.H.; McKenney, D.W.; Aubin, I.; Beardmore, T.; Beaulieu, J. [et al.]. 2012. **Placing forestry in the assisted migration debate.** BioScience. 62(9): 835–842. https://doi.org/10.1525/bio.2012.62.9.10.

Peters, M.P.; Prasad; A.; Matthews, S.N.; Iverson, L.R. 2020. **Climate change tree atlas, version 4.** Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. https://www.fs.usda.gov/nrs/atlas.

Prasad, A.; Pedlar, J.; Peters, M.P; McKenney, D.; Iverson, L.; Matthews, S.; Adams, B. 2020. **Combining U.S. and Canadian forest inventories to assess habitat suitability and migration potential of 25 tree species under climate change.** Diversity and Distributions. 26(9): 1142–1159. https://doi.org/10.1111/ddi.13078.

Sittaro, F.; Paquette, A.; Messier, C.; Nock, C.A. 2017. **Tree range expansion in eastern North America fails to keep pace with climate warming at northern range limits.** Global Change Biology. 23(8): 3292–3301. https://doi.org/10.1111/gcb.13622.

Swanston, C.W.; Janowiak, M.K.; Brandt, L.A.; Butler, P.R.; Handler, S.D. [et al.]. 2016. **Forest adaptation resources: climate change tools and approaches for land managers, 2nd ed.** Gen. Tech. Rep. NRS-GTR-87-2. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 161 p. https://doi.org/10.2737/NRS-GTR-87-2.

Williams, M.I.; Dumroese, R.K. 2013. **Preparing for climate change: forestry and assisted migration.** Journal of Forestry. 111(4): 287–297. https://doi.org/10.5849/jof.13-016.

Zhu, K.; Woodall, C.W.; Clark, J.S. 2012. **Failure to migrate: lack of tree range expansion in response to climate change.** Global Change Biology. 18(3): 1042–1052. https://doi.org/10.1111/j.1365-2486.2011.02571.x.

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