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Forest Management for Carbon Sequestration and Climate Adaptation

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Abstract

The importance of forests for sequestering carbon has created widespread interest among land managers for identifying actions that maintain or enhance carbon storage in forests. Managing for forest carbon under changing climatic conditions underscores a need for resources that help identify adaptation actions that align with carbon management. We developed the Forest Carbon Management Menu to help translate broad carbon management concepts into actionable tactics that help managers reduce risk from expected climate impacts in order to meet desired management goals. We describe examples of real-world forest-management planning projects that integrate climate change information with this resource to identify actions that simultaneously benefit forest carbon along with other project goals. These examples highlight that the inclusion of information on climate vulnerability, considering the implications of management actions over extended timescales, and identifying co-benefits for other management goals can reveal important synergies in managing for carbon and climate adaptation.

Keywords: climate adaptation, forest management, carbon, mitigation, climate vulnerability, carbon sequestration

Managing forest carbon stocks is critical for mitigating increasing atmospheric carbon dioxide concentrations. Although carbon stored in forests constitutes approximately 68 percent of US terrestrial carbon stocks (Liu et al. 2012, Liu et al. 2014), forest ecosystems comprise more than 90 percent of the land sector sequestration capacity (EPA 2016) and offset about 15 percent of total US fossil fuel emissions (Woodall et al. 2015). The strong mitigation potential of forest ecosystems makes carbon management a key component of proposed future natural climate solutions (Griscon et al. 2017, Fargione et al. 2018). However, a changing climate poses risks to the ability of forests to sequester carbon from rising temperatures, changing seasonality of precipitation, and increases in the frequency, severity, or extent of natural disturbance such as drought, wildfire,

Management and Policy Implications

Maintaining or enhancing ecosystem carbon storage is increasingly becoming an important goal for forest management. We developed the Forest Carbon Management Menu to identify a range of potential actions that adapt forests to a changing climate and benefit forest carbon by reducing climate-related carbon losses, sustaining forest health, or enhancing future productivity of forest ecosystems. This menu is intended to be used with other resources such as ecosystem vulnerability assessments and the Adaptation Workbook to help managers identify on-the-ground actions during the development of forest-management plans and projects. Additionally, the menu may assist policymakers interested in identifying carbon-friendly management practices for policies that support mitigation on forested landscapes or lands suitable for reforestation and agroforestry. This menu highlights the value to land managers and policymakers of considering extended timescales, climate risks, and potential cobenefits with other management goals for identifying synergies between adaptation and mitigation actions.

and forest pests and pathogens (Millar and Stephenson 2015, Williams et al. 2016, Seidl et al. 2017).

The importance of land stewardship for maintaining or enhancing forest carbon stocks is well recognized in the scientific literature. For example, past trends for terrestrial carbon stocks in the United States demonstrate the significance of forest regrowth following land clearing for agriculture in the eastern US (Birdsey et al. 2006), whereas recent analyses emphasize the current value of reforestation for increasing carbon in aboveground biomass (Sample 2017) and within soils (Nave et al. 2018). Other broad strategies for maintaining or enhancing forest carbon stocks have been proposed (e.g., Malmsheimer et al. 2008, Evans and Perschel 2009, Galik and Jackson 2009, Ryan et al. 2010, McKinley et al. 2011, Swift 2012), including avoiding conversion of forests to other land uses, minimizing forest disturbance, reducing carbon emissions, and increasing sequestration through enhanced forest growth. This broad literature reflects the wide variety of general strategies available to managers for maintaining or enhancing forest carbon. Translating these general strategies into specific actions at local scales helps land managers with implementation of adaptation plans (Anhalt-Depies et al. 2016, Woodruff and Stultz 2016). Although some examples of on-the-ground practices are included in this broad literature, to date there has not been a resource that compiles broad strategies for forest carbon management and translates these into on-the-ground actions. Translating broad adaptation concepts into prescriptive actions has been aided through development of resources that organize information into a tiered structure that clearly identifies desired outcomes (Swanston et al. 2016).

Identifying practices for managing forest carbon into the future calls for a recognition of the influences of a changing climate on forest ecosystems (Vose et al. 2018). For example, forests in the Midwest and Northeast are vulnerable to gradual changes from altered temperature and precipitation regimes, the shifting stressors from insect pests, invasive species, or forest pathogens, with the potential for rapid changes from alterations in small-scale natural disturbances (Swanston et al. 2018). Forests elsewhere in the United States may be most vulnerable to declines in health and productivity from increased frequency of large-scale disturbances, such as interactions between drought, insect pests, and wildfire (Stephens et al. 2018). The changing climate and its interaction with stressors may alter past carbon trends and responses to management in many places. These shifts may in turn complicate or even negate presumed best practices in carbon management, such that adaptation actions may be needed to maintain forest productivity and carbon stocks (Duveneck and Scheller 2016). Some previous syntheses of forest carbon-management strategies do not explicitly incorporate a changing climate, but there is thus a growing recognition that effective management of forests for carbon sequestration warrants consideration of future climate projections and expected impacts on ecosystems (Hof et al. 2017).

The Climate Change Response Framework[1] (CCRF) works to bridge the gap between broad-scale scientific information on potential climate change impacts on forests and the integration of this knowledge into forest-management planning to identify actionable practices (Janowiak et al. 2014, Ontl et al. 2018). The approach used by the CCRF relies on several resources, as described in Swanston et al. (2016). Managers work through an adaptive management process in the form of a step-by-step Adaptation Workbook. The workbook integrates region-specific climate change information with project-level considerations in order to identify on-the-ground adaptation actions to reduce climate risks and help meet management objectives. The Adaptation Workbook incorporates two complementary types of resources. The first includes assessments of climate-change impacts and vulnerability, such as regional forest ecosystem vulnerability assessments (Brandt et al. 2017), that inform users about climate-change impacts that may affect their area of interest. The second is a synthesis of climate-adaptation strategies and approaches organized to represent the continuum from broad concepts to specific actionable tactics (Janowiak et al. 2014). These "menus" of adaptation strategies and approaches outline potential management actions that managers can choose from, depending on project objectives, anticipated site-level climate impacts, and other project or organizational constraints and opportunities. Menus have been developed for forestry and urban forestry (Butler et al. 2012, Swanston et al. 2016), agriculture (Janowiak et al. 2016), and forested watershed management (Shannon et al. 2019). The *Practitioner's Menu of Adaptation Strategies and Approaches for Forest Carbon Management* was developed to provide a carbon-management resource for forest managers that includes an explicit integration of climate-change adaptation into broad-to-prescriptive forest carbon-management actions. Combining actions designed to reduce emissions from mortality and wildfire through the practice of climate adaptation with management actions designed to increase the rate of carbon sequestration represents a new bridging of climate adaptation and mitigation paradigms.

A Practitioner's Menu of Adaptation Strategies and Approaches for Forest Carbon Management

We developed this resource to meet the growing need for a resource that provides managers with a comprehensive set of adaptation strategies and approaches to assist in identifying appropriate practices for carbon management. Similar to our previously published menus, the Forest Carbon Management Menu (Menu) is organized hierarchically and describes a range of potential actions that can be taken based on site conditions, forest vulnerability, and the needs of managers. The strategies and approaches within the Menu include actions that aim to maintain existing on-site carbon (defensive actions) and actions that seek to enhance the capacity of forests to capture carbon into the future (offensive actions). These actions must first align with the management objectives for the site, but their suitability will be further judged in relation to the vulnerability determination, site conditions, and the user's risk tolerance. For example, managers might choose a set of offensive actions that aim to increase future carbon gains in an understocked forest determined to have low vulnerability to disturbance losses into the future. In contrast, managers working in a well-stocked forest with low vulnerability to future disturbance might choose to take a defensive approach in order to maintain existing conditions if they have low risk tolerance or decide to increase basal area with a set of more offensive approaches if they have a higher risk tolerance. Importantly, the Menu only considers carbon stored within ecosystems and does not consider off-site carbon storage, such as carbon stored in harvested wood products or the carbon benefits from substituting fossil fuels with wood energy.

The Menu was developed following a review of over 200 published peer-reviewed papers and reports on broad strategies for carbon management in forests, impacts of specific silvicultural practices on forest carbon stocks, climate adaptation, and climate and disturbance impacts on forest carbon. This literature review focused on available scientific information for temperate and boreal forests in North America with an emphasis on eastern forest types, but included consideration of climate stressors, disturbance risks, and management actions relevant for forests in the western US as well. The resulting Menu includes seven broad "strategies" that contain 31 "approaches" (Table 1). The Menu's full narrative, including examples of on-the-ground tactics and supporting citations, is available as a supplementary resource (S1).

Application of the Forest Carbon-Management Menu

Numerous demonstration projects that serve as real-world examples of climate adaptation in forest management have been developed with public, private, nongovernment, and tribal land managers through the CCRF (Janowiak et al. 2014, Brandt et al. 2016, Swanston et al. 2016, Ontl et al. 2018). Here, we summarize two demonstration projects developed using the Menu to identify actions that enhance the ability of a particular forest ecosystem to both adapt to anticipated changes and sequester carbon into the future. These projects show the application of climate adaptation for carbon benefits in contrasting scenarios: an update to a management plan in a low-vulnerability

Table 1. Menu of adaptation strategies and approaches for forest carbon management.

- Strategy 1: Maintain or increase extent of forest ecosystems
  - 1.1 Avoid forest conversion to nonforest land uses
  - 1.2 Reforest lands that have been deforested and afforest suitable lands
  - 1.3 Increase the extent of forest cover within urban areas
  - 1.4 Increase or implement agroforestry practices
- Strategy 2: Sustain fundamental ecological functions
  - 2.1 Reduce impacts on soils and nutrient cycling
  - 2.2 Maintain or restore hydrology
  - 2.3 Prevent the introduction and establishment of invasive plant species and remove existing invasives
  - 2.4 Maintain or improve the ability of forests to resist pests and pathogens
  - 2.5 Reduce competition for moisture, nutrients, and light
- Strategy 3: Reduce carbon losses from natural disturbance, including wildfire
  - 3.1 Restore or maintain fire in fire-adapted ecosystems
  - 3.2 Establish natural or artificial fuelbreaks to slow the spread of catastrophic fire
  - 3.3 Alter forest structure or composition to reduce the risk, severity, or extent of wildfire
  - 3.4 Reduce the risk of tree mortality from biological or climatic stressors in fire-prone systems
  - 3.5 Alter forest structure to reduce the risk, severity, or extent of wind and ice damage
- Strategy 4: Enhance forest recovery following disturbance
  - 4.1 Promptly revegetate sites after disturbance
  - 4.2 Restore disturbed sites with a diversity of species that are adapted to future conditions
  - 4.3 Protect future-adapted seedlings and saplings
  - 4.4 Guide species composition at early stages of development to meet expected future conditions
- Strategy 5: Prioritize management of locations that provide high carbon value across the landscape
  - 5.1 Prioritize low-vulnerability sites for maintaining or enhancing carbon stocks
  - 5.2 Establish reserves on sites with high carbon density
- Strategy 6: Maintain or enhance existing carbon stocks while retaining forest character
  - 6.1 Increase structural complexity through retention of biological legacies in living and dead wood
  - 6.2 Increase stocking on well-stocked or understocked forest lands
  - 6.3 Increase harvest frequency or intensity because of greater risk of tree mortality
  - 6.4 Disfavor species that are distinctly maladapted
  - 6.5 Manage for existing species and genotypes with wide moisture and temperature tolerances
  - 6.6 Promote species and structural diversity to enhance carbon capture and storage efficiency
  - 6.7 Use seeds, germplasm, and other genetic material from across a greater geographic range
- Strategy 7: Enhance or maintain sequestration capacity through significant forest alterations
  - 7.1 Favor existing species or genotypes that are better adapted to future conditions
  - 7.2 Alter forest composition or structure to maximize carbon stocks
  - 7.3 Promote species with enhanced carbon density in woody biomass
  - 7.4 Introduce species or genotypes that are expected to be adapted to future conditions

Note: The full menu narrative can be found in the Supplementary Material (S1).

northern hardwoods forest in northern Vermont, and reforestation planning in a high-vulnerability forest impacted by past disturbance and current changes in climate in northern Minnesota.

Audubon Vermont's Green Mountain Audubon Center

Staff from Audubon Vermont and the Vermont Agency of Natural Resources collaborated to update the management plan on Audubon Vermont's Green Mountain Audubon Center (GMAC) in northwest Vermont. The project team used the Adaptation Workbook to identify actions that benefit bird habitat on the property while also enhancing carbon storage and supporting GMAC's significant environmental education, scientific research, and outdoor recreation opportunities. GMAC serves as a demonstration area for the *Foresters for the Birds* program, which provides tools and training for forest and natural-resource professionals to help landowners integrate management of timber and migratory bird habitat.

Define Location, Project, and Time Frames

The 255-acre GMAC property encompasses wetlands, streams, meadows, and forests of conifer and northern hardwood species. Forest stands are a mixture of upland northern hardwood (sugar maple, red maple, and white ash dominant) and mixed wood (white pine and eastern hemlock dominant) cover types. A 10-acre sugarbush with an overstory dominated by sugar and red maple is used for educational purposes. Like much of the region, most of GMAC's forests established following agricultural abandonment around 100 years ago, with little or no forest management occurring since that time.

The primary management goal for this property is to maintain a mosaic of habitat types for all wildlife, with a focus on forest bird species. Active forest management has recently been implemented at the GMAC to demonstrate bird-friendly land-management practices[2]. Management objectives for wildlife habitat include maintaining a diversity of seral stages, maintaining interior forest conditions (75–80 percent canopy cover) where they occur, and enhancing structural heterogeneity and understory development. Additional management goals include increasing sawtimber quality, quantity, and volume increment for on-site use, maintaining trails and access for recreation, and promoting sugar maple regeneration and canopy development within the sugarbush by improving forest health.

Assess Site-Specific Impacts and Vulnerabilities

A vulnerability assessment for regional forest ecosystems (Janowiak et al. 2018) was used to identify potential climate change effects across the region. The project team combined this broad-scale information with their knowledge of the local landscape to identify climate risks specific to the GMAC. The team was concerned that some northern tree species common across the property are projected to decline as a result of a warming climate. Further, a warmer climate reduces the occurrence of the low lethal temperatures that control non-native insect pests such as hemlock wooly adelgid and emerald ash borer (Weed et al. 2013). These species are not currently present but are expected to expand into the area in the future from climate warming, making the abundant large-diameter hemlock and scattered white ash on the property vulnerable to loss. The team had concerns over increased non-native invasive plant species that may decrease the abundance of insect food resources for birds critical during the nesting season and prior to migration. Additionally, greater frequency of extreme weather events that can cause wind disturbance and intense precipitation may result in larger and more frequent natural disturbances, resulting in the creation of more early-successional and young forest habitats, soil erosion, and impacts on the property's stream and wetland communities. These disturbances can further promote the spread of non-native invasive plants that decrease habitat value for songbirds nesting in mature forests (Hayes and Holzmueller 2012). The region is already experiencing shorter and warmer winters as a result of climate change (Stager and Thill 2010), a trend that creates challenges for winter harvesting (Rittenhouse and Rissman 2016) in areas of the property where saturated soil conditions and the potential for disturbance and soil carbon loss (Nave et al. 2010) limit summer harvesting.

Evaluate Management Objectives Given Projected Impacts and Vulnerabilities

The project team highlighted several challenges for maintaining healthy forest conditions for both bird habitat and carbon storage because of the potential for increased forest disturbance from extreme weather and decline of northern species as a result of climate change. Additionally, the potential for loss or substantial decline in abundance of some important tree species creates significant concerns for maintaining both wildlife habitat and carbon sequestration and storage. For example, the property's many large-diameter eastern hemlock and eastern white pine provide unique value for forest bird habitat such that the loss or decline in abundance of these trees would have a disproportionately negative impact on forest bird habitat. These changes would also reduce the potential of the forests at the GMAC to sequester carbon and even result in forests becoming a source of carbon to the atmosphere (Duveneck and Scheller 2016, Krebs et al. 2017). In addition to concerns about increases in forest pests in a changing climate, shorter and milder winters favor the growth of deer populations, resulting in browsing pressure that reduces understory diversity and regeneration success. Increases in extreme storms and forest disturbance also create pathways for the invasion of non-native plant species, which can reduce native tree species diversity and subsequently bird species diversity. Extreme storms also present operational challenges for maintaining recreational trails because of erosion and windthrow, requiring expensive or time-consuming trail repair and rerouting. Past land use and a previous lack of forest management at the GMAC have created a forest that is largely even-aged. The

Table 2. Selected adaptation tactics and associated approaches for The Green Mountain Audubon Center identified using the Forest Carbon Management Menu, with associated cobenefits for forest bird habitat, climate adaptation, and carbon mitigation.

Tactic	Approach(es)	Anticipated cobenefits
Maintain current extent of forested area, including early-successional and mature forest	1.1 Avoid forest conversion to nonforest land uses	Forest bird habitat: Maintains extent and quality of bird habitat Climate adaptation: Maintains existing tree species diversity Carbon mitigation: Maintains existing carbon sequestration capacity
Using forwarder during harvest operations and position landing sites adjacent to the road (rather than within forest)	2.1 Reduce impacts on soils and nutrient cycling	Forest bird habitat: Maintains interior forest bird habitat Climate adaptation: Minimizes nonclimate stressors; reduces risk of erosion during extreme rain events Carbon mitigation: Protects soil carbon stocks
Control of non-native invasive plant populations using mechanical removal (preferred), herbicides, or targeted goat grazing	2.3 Prevent the introduction and establishment of invasive plant species and remove existing invasives 2.5 Reduce competition for moisture, nutrients, and light	Forest bird habitat: Native plant populations support greater insect food resources and higher-quality cover Climate adaptation: Maintains native plant diversity, which enhances forest resistance and resilience Carbon mitigation: Maintains carbon sequestration capacity of forest lands and natural ecosystems
If EAB impacts occur, use insecticide on a small number of ash trees to preserve ash component on landscape	2.4 Maintain or improve the ability of forest to resist pests and pathogens	Forest bird habitat: Increases tree species diversity and potential food resources for birds Climate adaptation: Increases opportunities for species diversity recovery in the future Carbon mitigation: Reduces carbon losses, potentially enhances future carbon gains
Maintain no-harvest reserve area where forest is allowed to succeed to larger size classes	4.2 Establish reserves on sites with high carbon density	Forest bird habitat: Provides old-forest interior bird habitat Climate adaptation: Maintains landscape diversity; potential refugia Carbon mitigation: Maintains carbon in high carbon density stands
Implement forest harvest (such as group selection and expanding gap harvests) in northern hardwood stands and in sugarbush to maintain or increase tree species diversity and improve tree growth	2.4 Maintain or improve the ability of forest to resist pests and pathogens 3.5 Alter forest structure to reduce severity or extent of wind and ice damage 6.6 Promote species and structural diversity to enhance carbon capture and storage efficiency	Forest bird habitat: Increases vertical structure, providing more cover and nesting sites Climate adaptation: Improves tree health and vigor to enhance forest resistance and resilience to a variety of climate-related stressors Carbon mitigation: Improves tree health and vigor of the residual stand to maintain long-term carbon stocks and maintain/enhance sequestration rates

Table 2. Continued

Tactic	Approach(es)	Anticipated cobenefits
In actively managed stands, use silvicultural practices (single-tree selection, crop-tree release, and thinnings) that promote the quality of red maple, white pine, black cherry, and other native species for sawtimber	5.1 Prioritize sites with low vulnerability to carbon loss for maintaining high carbon density 7.1 Favor existing species or genotypes that are better adapted to future conditions	Forest bird habitat: Increases habitat quality and complexity through enhanced species and structural diversity Climate adaptation: Promotes native species that are expected to be better adapted to future conditions Carbon mitigation: Reduces risk of long-term carbon losses by favoring lower-risk species; may increase provision of long-lived wood products
In actively managed stands, increase stocking levels by allowing trees to get to larger size classes	6.2 Increase stocking on well-stocked or understocked forest lands	Forest bird habitat: Maintains interior forest bird habitat Climate adaptation: Maintains structural diversity Carbon mitigation: Increases carbon stocks within managed stands
Promote northern red oak component in areas where the species is present	6.6 Promote species and structural diversity to enhance carbon capture and storage efficiency	Forest bird habitat: Increases tree species diversity and potential food resources for birds Climate adaptation: Promotes native species that are expected to be better adapted to future conditions Carbon mitigation: Reduces risk of long-term carbon losses by favoring lower-risk species

project team identified tree mortality from insect pests and wind disturbance as opportunities for increasing snags and downed wood that enhances structural diversity of the forest, and benefitting both carbon and bird habitat.

Identify adaptation approaches and tactics for implementation

A review of current management practices concluded that many activities that have been implemented through *Foresters for the Birds* programming provide an array of benefits—including bird habitat, timber, and carbon—while increasing the ability of the forest to adapt to changing conditions (Table 2). The project team felt that the forest ecosystems at the GMAC had low to low-moderate vulnerability to climate-change impacts, which were reflected by identifying some stands as no-harvest reserves (Approach 5.2) for interior forest bird habitat that additionally support maintaining high densities of carbon. Thinking about adaptation and carbon benefits guided the project team to consider additional forest stands that were not originally identified in the management plan update. The team identified a set of nonsilvicultural management actions, which included tactics for controlling invasive plant species and targeted insecticide treatments for selected ash trees (Flower et al. 2018) if emerald ash borer arrives (Approaches 2.3, 2.4), to implement in the additional stands. The project team highlighted that the Menu helped them to envision management at the GMAC through the lens of carbon sequestration and climate adaptation in addition to their focus on managing for interior songbird habitat. This new perspective led to the identification of active management tactics that take a "defensive" approach to maintaining and protecting current forest carbon stocks. For example, significant concerns with the impacts of insect pests, invasive plants, and disturbance from extreme storms were reflected in several tactics that enhance forest health to maintain existing carbon stocks by actively promoting a diversity of tree species, age classes, and structure (Strategy 6). These adaptation approaches aim to reduce the long-term risks to carbon stocks and degradation of forest bird habitat that could occur from widespread forest decline. Promoting species diversity and managing for existing species expected to be adapted to future conditions (Approach 7.1) addressed the key impacts associated with declining habitat suitability of some tree species and the anticipated risks to the goals of maintaining forest birds, recreational opportunities, and maple syrup production. In particular, managing for increased abundance of red oak, a future-adapted species for the site, will support an increased richness of insect food resources (Tallamy and Shropshire 2009) for sustaining diverse bird communities (Rodewald and Abrams 2002) while maintaining or increasing carbon residence time.

Monitor and Evaluate Effectiveness of Implemented Actions

Monitoring efforts initially identified by the project team focused on continued efforts for detecting and removing invasive plant species, erosion on trails, and detection of non-native insect pests. Additionally, the regeneration of tree species will be assessed, particularly in harvested gaps. These efforts will augment the continuing monitoring of forest birds at the GMAC.

Reforestation in Minnesota's Split Rock Lighthouse State Park

Many forests along Minnesota's North Shore are in a degraded condition, with old and dying paper birch (*Betula papyrifera*) and aspen (*Populus tremuloides*) stands that are highly vulnerable to transitioning to brush and grass (Handler et al. 2014, Moser et al. 2015). Logging followed by severe fires in the early 1900s resulted in the replacement of the conifer-dominated forest with birch and aspen, and the recent combination of increasing stress from extensive deer browsing, drought, insect pests and diseases, and increasing grass cover has limited tree regeneration (NSFC 2015). The Minnesota Department of Natural Resources (MN DNR) and The Nature Conservancy in Minnesota have initiated a collaborative project for reforesting thousands of acres in the North Shore Highlands of Lake Superior in Northeast Minnesota. More than 2,200 acres located across seven State Parks were identified as having good potential for reforestation. Scientists and forest managers from these partnering organizations used the Adaptation Workbook along with the Forest Carbon Management Menu for planning efforts for one of the sites, a 140-acre parcel of degraded and understocked aspen–birch forest in Split Rock Lighthouse State Park.

Define Location, Project, and Time Frames

Split Rock Lighthouse State Park is managed by the MN DNR to preserve, perpetuate, and interpret natural features as mandated by state statutes[4]. Part of this mandate is achieved through restoring desirable species and ecological communities. Given this directive, long-term management goals for the project area include establishing resilient natural communities and providing habitat for rare species and species of greatest concern by promoting an older forest with a complex structure and high tree-species diversity. The collaboration between The Nature Conservancy and MN DNR focused on planning for reforestation, with the additional benefits of carbon sequestration. These carbon stock gains would greatly increase sequestration on the project area relative to the current condition of the forest that, without intervention, will likely continue to decline from age-related mortality and be replaced by woody shrubs and grass. Two sites were selected totaling 140 acres; site A is a high-use area adjacent to roads, trails, buildings, and a campground, whereas site B is a natural area not significantly impacted by park visitor use (Figure 1).

Assess Site-Specific Impacts and Vulnerabilities

Members of the project planning team were primarily concerned with warming temperatures—particularly in the winters—that are expected to intensify the existing stressors limiting tree regeneration at the site, such as deer herbivory and forest pests and diseases (Handler et al. 2014). In particular, less-severe winters may allow deer populations to rise, increasing the already-high deer densities along the north shore and exacerbating impacts on forest regeneration. Additionally, more frequent periods of soil moisture stress might increase as a result of warmer conditions and increased vapor pressure deficit in the region (Angel et al. 2018), with the effect of these drier conditions intensifying for trees growing on the shallow, rocky soils at Spilt Rock Lighthouse State Park. Correspondingly, these soil conditions contribute to the site's vulnerability to erosion from extreme precipitation events, which are becoming more frequent (USGCRP 2017).

Evaluate Management Objectives Given Projected Impacts and Vulnerabilities

Climate change creates notable challenges and opportunities for this reforestation project. First and foremost, future climate conditions may be unsuitable for the aspen–birch forest type that has occupied this site for the past several decades; this boreal forest type is

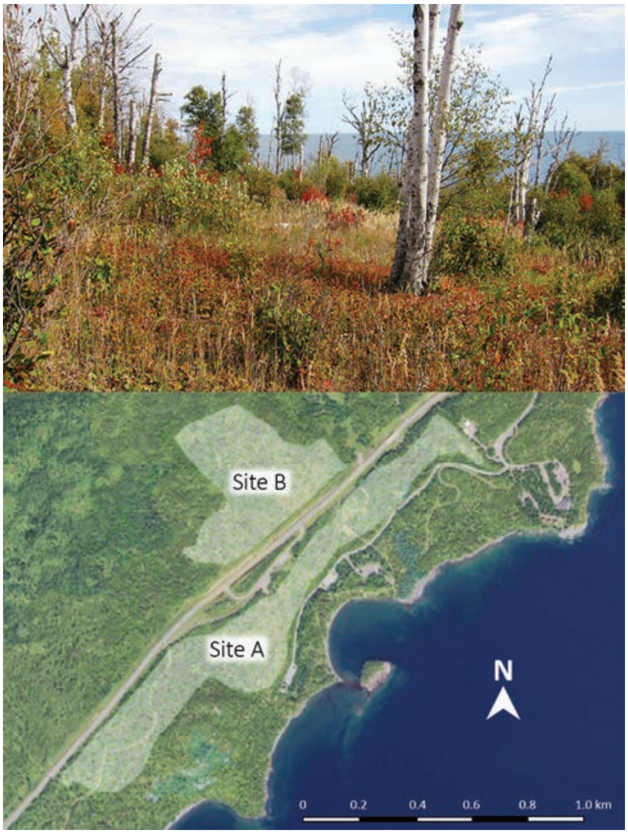

Figure 1. Top: dying birch and aspen forest at risk of transitioning to grass and shrub cover because of a lack of tree regeneration along Minnesota's north shore of Lake Superior (image permission of Chel Anderson/ Minnesota Conservation Volunteer). Bottom: map of the locations of two reforestation project areas within Split Rock Lighthouse State Park. Site A is a high visitor use area; site B is a natural area less impacted by park visitors (map courtesy of Samuel Reed).

one of the most vulnerable to climate change (Handler et al. 2014). Additional challenges for the goal of reforesting this site are the major impact of deer herbivory on tree seedling survival, as well as the presence of several insect pests and diseases (e.g., the bronze birch borer [*Agrilus anxius*], white pine blister rust). These major challenges point toward the overall opportunity to reforest the area using species that will be adapted to current and future climate conditions. The project team identified the proximity of the site to Lake Superior and the potential moderating effects on temperature extremes (Anderson et al. 2018) as an opportunity to include in the reforestation efforts long-lived conifer species, such as white cedar (*Thuja occidentalis*) and white spruce (*Picea glauca*), that historically were present at the site and may otherwise experience declining habitat suitability elsewhere in the region.

Identify Adaptation Approaches and Tactics for Implementation.

Prior to using the Menu with the Adaptation Workbook, the project team had identified a general reforestation approach for carbon sequestration at both sites A and B that included site preparation to reduce competition from brush followed by planting native conifers, protecting these seedlings from deer browsing, and postplanting release from competing vegetation using brush saws or spot application of herbicides. Some of these previously planned tactics were identified in the Menu (Approaches 1.2, 2.5, 4.3, 6.2), highlighting that these actions address climate risks and associated stressors. As a result of using the Menu (Table 3), the project team adjusted some current tactics as well as brainstormed new tactics not identified in the original reforestation plans. For example, the team adjusted criteria for conifer planting site selection to favor north-facing slopes and draws (Approach 5.1), as these are low-vulnerability sites with increased likelihood of conifer establishment. New tactics included retaining healthy individuals of birch and aspen (Approach 6.1), which reflect the desired carbon benefits from maintaining species diversity and retaining biological legacies in living and dead wood for maintaining carbon stocks. Additionally, the intention to promote forest stands with complex structure, high species diversity, and the ability to resist existing pests and pathogens was reflected in tactics that included planting additional species throughout the project area (Strategy 6 and Approach 2.4). These are species expected to be better adapted to future conditions (e.g., red maple and yellow birch) that can also have greater carbon densities in wood than conifers. Planting southern genotypes of red oak and other future-adapted species present in the region (Approaches 6.7, 7.1) was recommended for site A (Figure 1), where guidelines for restoration in high visitor-use areas allow some flexibility for introducing future-adapted genotypes and species that were not historically present at the site. This tactic addresses the project team's concerns about increasing soil moisture stress on the shallow rocky soils of the project area. Planting southern species or southern genotypes of existing species was considered but was not recommended for site B because agency guidelines for assisted migration related to native plant communities are not yet completed. Likewise, introducing future-adapted species that are not present in the region (Approach 7.4) was considered as a tactic, but ultimately rejected for the project area. It is expected that these guidelines will continue to undergo revisions based on the recognition of increasing challenges to

Table 3. Selected adaptation tactics and associated approaches for Split Rock Lighthouse State Park identified using the Forest Carbon Management Menu, with associated cobenefits for climate adaptation and carbon mitigation.

Tactic	Approach(es)	Anticipated cobenefits
Conduct site preparation in advance of planting by brush-sawing and/or shearing across portions of reforestation sites with heavy brush	2.5 Reduce competition for moisture, nutrients, and light 4.3 Protect future-adapted seedlings and saplings	Climate adaptation: Creates conditions favorable to planting future-adapted tree species Carbon mitigation: Creates conditions suitable for growing a more productive forest
Retain individual healthy trees within reforestation areas to serve as legacy trees	6.1 Increase structural complexity through retention of biological legacies in living and dead wood 6.5 Manage for existing species and genotypes with wide moisture and temperature tolerances	Climate adaptation: Retained trees increase forest complexity or diversity, may provide a seed source of future-adapted tree species Carbon mitigation: Legacy trees can increase forest carbon storage
Plant tree seedlings at a rate of approximately 460 trees per acre to reforest the site	1.2 Reforest lands that have been deforested and afforest suitable lands 6.2 Increase stocking on well-stocked or understocked forest lands	Climate adaptation: Increases tree species diversity, which enhances forest resistance and resilience Carbon mitigation: Maintains extent of forest lands and natural ecosystems in support long-term sequestration
Within planted areas, use a diverse mixture of tree seedlings, such as white pine, red maple, and yellow birch	2.4 Maintain or improve the ability of forest to resist pests and pathogens 4.2 Restore disturbed sites with a diversity of species that are adapted to future conditions 6.6 Promote species and structural diversity to enhance carbon capture and storage efficiency 7.2 Alter forest composition or structure to maximize carbon stocks	Climate adaptation: Increases tree species diversity, which enhances forest resistance and resilience Carbon mitigation: Increases in tree species diversity can increase the amount of carbon that can be stored within a forest
Within plantings, include native conifer species (e.g., white spruce, white pine, and northern white cedar). Additionally, increase the density of conifers planted on north-facing slopes and in draws	1.2 Reforest lands that have been deforested and afforest suitable lands 5.1 Prioritize low-vulnerability sites for maintaining or enhancing carbon stocks 6.2 Increase stocking on well-stocked or understocked lands	Climate adaptation: Increases tree species diversity, which enhances forest resistance and resilience Carbon mitigation: Increases in tree species diversity can increase the amount of carbon that can be stored within a forest
Within plantings, include oak and southern genotypes of existing native tree species (site A)	6.7 Use seeds, germplasm, and other genetic material from across a greater geographic range 7.1 Favor existing species or genotypes that are better adapted to future conditions	Climate adaptation: Promotes species that are expected to be better adapted to future conditions Carbon mitigation: Reduces risk of future carbon losses by favoring lower-risk species
Protect tree seedlings from deer browse using fencing, tree shelters, and bud caps	4.3 Protect future-adapted seedlings and saplings	Climate adaptation: Promotes species that are expected to be better adapted to future conditions Carbon mitigation: Enhances carbon sequestration by limiting seedling damage or mortality

Table 3. Continued

Tactic	Approach(es)	Anticipated cobenefits
Release seedlings using brush-cutting or spot application of herbicide where plantings are crowded	2.5 Reduce competition for moisture, nutrients, and light	Climate adaptation: Promotes species that are expected to be better adapted to future conditions Carbon mitigation:: Enhances carbon sequestration by limiting seedling damage or mortality
Following successful reforestation, allow for natural forest growth without harvest	6.2 Increase stocking on well-stocked or understocked forest lands	Climate adaptation: Increases species and structural diversity Carbon mitigation: Allows for long-term forest carbon sequestration
Fire is unlikely to cause large-scale carbon loss because of access and infrastructure at site A	5.1 Prioritize sites with low vulnerability to carbon loss for maintaining high carbon density	Climate adaptation: Reduces risk of fire spread to planting sites Carbon mitigation: Reduces risk of catastrophic carbon loss from fire
Do postplanting “firewise” treatments around planting sites with greater fire risk	3.2 Establish natural or artificial fuelbreaks to slow the spread of catastrophic fire	Climate adaptation: Reduces risk of fire spread to adjacent sites Carbon mitigation: Reduces risk of catastrophic carbon loss from fire
Include high carbon density species in retention and planting, such as oak species and red maple	7.3 Promote species with enhanced carbon density in woody biomass	Climate adaptation: Increases species and structural diversity Carbon mitigation: Allows for long-term forest carbon sequestration

restoring presettlement forest composition from climate change (Boulanger et al. 2019).

Monitor and Evaluate Effectiveness of Implemented Actions.

The project team identified monitoring metrics to determine the effectiveness of the project. Survival and growth of planted seedlings will be assessed annually for 3 years following planting, and every 2 years thereafter until establishment. Persistence and size of legacy trees of aspen and birch will also be monitored for the duration of the project. Finally, composition and density of natural regeneration will be assessed periodically to assess likely future trajectories of forest succession within planting sites.

Conclusion

The development of the Forest Carbon Management Menu and the case studies demonstrating its use in real-world forest-management planning highlight three important considerations for planning adaptation actions for effective forest carbon management.

Considering Extended Time Scales Can Reveal Synergies between Adaptation and Mitigation

Forest management that involves the removal of tree biomass inherently results in an immediate reduction in carbon stocks. Many adaptation tactics, such as thinning a stand to increase drought resistance, can be viewed as being at odds with mitigation goals because of the short-term negative impacts on stand-level carbon stocks. The perception of a contradiction between adaptation and mitigation goals, however, does not take into account the carbon balance implications of these actions across decadal timescales. Ideally, evaluation of the potential tradeoffs accounts for the anticipated long-term changes in carbon fluxes. Although carbon stocks in some harvested forest stands may take many decades to recover to preharvest levels (Powers et al. 2012), in some forest stands the release from competition in advanced regeneration or older trees may increase annual increment of residual trees (Hoover and Stout 2007), reducing the time required for stand-level carbon stocks to recover. Managers can understand changes in carbon stocks over time, both in unmanaged areas and resulting from various silvicultural practices from establishing baseline carbon estimates using forest inventory data (Smith et al. 2004).

Consideration of Climate Vulnerability May Increase the Effectiveness of Management Actions on Enhancing Forest Carbon

Forest disturbances exert a major influence on forest carbon stocks and uptake (Williams et al. 2016), so reducing the risks of carbon loss from natural disturbance is critical for maintaining or enhancing carbon stocks in forests over extended time spans. Management actions that decrease total carbon storage at a site in the short-term in order to reduce the vulnerability to large carbon losses may ultimately have a net positive impact on carbon residence time. These actions may encourage fewer, larger, more vigorous trees that are less prone to drought-induced declines in productivity (Bottero et al. 2017); shift composition of a stand to more future-adapted species; or increase the structural complexity of a site to increase the site resilience to certain biotic stressors. Practices that reduce ecosystem vulnerability while minimizing short-term carbon loss may be best able to maximize a site's capacity for carbon storage over long temporal scales.

Determination of a site's vulnerability to carbon losses from climate-related disturbances is critical in evaluating the carbon implications of forest management and determining suitable actions for carbon benefits. Increasing basal area within a stand through limiting or delaying biomass harvest has a direct carbon benefit in managed forests. For example, extending rotation length in even-aged management systems and increasing the time between harvest entries in uneven-aged systems have been frequently suggested as strategies that lead to greater on-site carbon storage (Sohngen and Brown 2008, Foley et al. 2009, Ryan et al. 2010, McKinley et al. 2011). These practices are often included in scientific syntheses of forest carbon management, but integrating climate risk into the assessment of these practices is uncommon (although see Galik and Jackson 2009). Although extending rotations may provide carbon benefits on low-vulnerability sites, some studies suggest shortening rotations or reducing stocking levels in high-vulnerability forests may provide greater carbon benefits. Shortening rotations may reduce risk of large carbon loss when disturbance does occur (Irland 2000, González et al. 2005, Wang et al. 2013), and reduced stocking levels may decrease the incidence of tree mortality, for example by reducing drought susceptibility (D'Amato et al. 2013, Bottero et al. 2017) or damage from wind and ice storms (Balch 2014). Additionally, shorter rotations and reduced stocking provide more management flexibility, such as the ability to transition to more future-adapted species or increase the structural diversity within stands (O'Hara and Ramage 2013, Thom et al. 2017). Land managers interested in evaluating the carbon benefits of certain management practices under future climate scenarios may consider working with partners with expertise in forest landscape simulation modeling using LANDIS-II (Gustafson et al. 2006). Similarly, the Forest Vegetation Simulator is a forest growth model with a climate extension (Climate-FVS) that incorporates the effects of climate change currently available for managers working in western United States forest types (Crookston et al. 2010).

Carbon Is Often One of Many Desired Forest Benefits

Managing forests for maintaining or enhancing carbon stocks is receiving increasing interest from forest landowners and land-management agencies (McNulty et al. 2018, Peterson St-Laurent et al. 2018) as the impacts from a changing climate intensify. Forests provide a wide diversity of benefits to society, and correspondingly landowners and practitioners choose a diversity of adaptation strategies when managing to reduce climate risks (Ontl et al. 2018; CCRF[3]). Tradeoffs between multiple objectives for some management actions are often recognized, such as the tradeoffs between carbon storage and desired economic or ecological outcomes (Gutrich and Howarth 2007, Johnston and Withley 2017). For example, the value of early-successional ecosystems for biodiversity and habitat may be limited when rapid reforestation for carbon sequestration is implemented, whereas forest analyses of optimal management for timber supply and carbon may best be pursued in separate stands for some locations (Seidl et al. 2007). However, practices that can provide benefits for multiple management objectives may create added efficiency. Adaptation actions conducive to both carbon storage and other forest values, such as improving wildlife habitat or water quality, may increase the cost-effectiveness of management practices and are likely to be desirable across a diversity of forest ownerships.

The Forest Carbon Management Menu complements the existing Adaptation Workbook that has been used by many land managers across diverse land ownership types to help successfully incorporate climate change adaptation into on-the-ground activities. Just as the original Forestry Menu has helped managers explicitly identify the adaptation intention of their on-the-ground actions in hundreds of projects, the Forest Carbon Management Menu helps managers identify the intersecting mitigation and adaptation intention of their actions. The case studies described here show that the use of the Menu helps translate broad adaptation ideas into tangible forest-management actions for maintaining or enhancing forest carbon over decadal timescales. Using the Menu together with the Adaptation Workbook provides an opportunity to incorporate climate vulnerability in order to identify site-appropriate tactics that enhance the ability of the ecosystem to adapt to anticipated changes for long-term carbon mitigation while providing significant cobenefits for additional management goals.

Supplementary Materials

Supplementary data are available at *Journal of Forestry* online.

Supplement 1. Full narrative and literature citations of the *Practitioner's Menu of Adaptation Strategies and Approaches for Forest Carbon Management*.

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Endnotes

1. Find more information at www.forestadaptation.org.
2. For more information on the *Foresters for the Birds* program, visit www.vt.audubon.org/conservation/foresters-birds.
3. For details on Climate Change Response Framework adaptation demonstration projects, see www.forestadaptation.org/demonstration-projects.
4. Details on Minnesota statutes pertaining to State Parks can be found at www.revisor.mn.gov/statutes/cite/86A.05.

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