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

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Forests play a critical role in sequestering carbon from the atmosphere, helping mitigate rising atmospheric carbon dioxide (CO_2) levels. This forest carbon sink offsets nearly 15 percent of total U.S. fossil fuel emissions (Woodall et al. 2015), comprising more than 90 percent of the U.S. land sector sequestration capacity (EPA 2016). Forest management actions are necessary to support maintaining or enhancing forests as carbon sinks, particularly as forest mortality and stressors increase from a changing climate (McKinley at al. 2011).

To support land managers interested in maintaining or enhancing forest carbon stocks and the capacity to sequester additional carbon into the future, decision makers need tools and resources to assist in translating broad concepts of carbon management into specific, tangible actions. This menu of **adaptation strategies and approaches for forest carbon management** provides options for actions to support integrating climate change considerations into carbon management activities. The strategies and approaches are derived from a wide range of reports and peer-reviewed publications on climate change adaptation and carbon management and serve as intermediate "stepping stones" for translating broad concepts into targeted and prescriptive tactics for implementation. These are intended to be used with an **Adaptation Workbook** (Swanston et al. 2016 - *Forest Adaptation Resources: Climate change tools and approaches for land managers and Adaptation Workbook, 2nd edition;* and the corresponding online interactive tool: adaptationworkbook.org), which provides a structured, adaptive approach for integrating climate change considerations into planning, decision-making, and implementation.

This resource is designed as a flexible approach (rather than specific guidelines or recommendations) to accommodate diverse geographic settings, local site conditions, and other management or policy considerations. For these reasons, this set of adaptation strategies and approaches serves as a menu of **potential** carbon management actions that supports land managers in developing and implementing their own specific actions. Although menu items can be applied in various combinations to achieve desired outcomes, not all items on the menu will work together. Furthermore, actions that work well in one forest or community type may not work in another; it is up to the land manager to select appropriate actions for a specific project and specific conditions. Importantly, the carbon management strategies and approaches presented are intended to build upon current management actions that work to sustain forests over the long term. A changing climate may compel some managers to adopt new practices, but it is equally important to review existing management practices through the filter of climate change adaptation to ensure that they remain suitable and will be sustainable.

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The focus of the forest carbon management menu is to aid managers in planning land management actions for enhancing carbon within forested ecosystems, however many of the strategies and approaches outlined here can apply to urban and agricultural settings as well. These lands have been considered in the development of this menu within the context of the importance of tree canopy cover for carbon stocks, however we recognize there will be many strategies and approaches for managing for carbon not included, such as actions for soil or crop management (e.g. tillage, cropping systems, grazing, etc.). Additionally, this menu does not consider carbon benefits of harvested wood products, but only considers carbon stocks and sequestration within forests.

The menu of adaptation strategies and approaches can provide:

- A broad spectrum of possible adaptation actions that can help sustain healthy ecosystems and achieve management goals in the face of climate change
- A framework of adaptation actions from which managers select actions best suited to their specific management goals and objectives
- A platform for discussing climate change-related topics and adaptation methods
- Examples of tactics that could potentially be used to implement an approach, recognizing that specific tactics will be designed by the land manager.

The menu of adaptation strategies and approaches does not:

- Make recommendations or set guidelines for management decisions. It is up to the land manager to decide how this information is used.
- Express preference for any strategies or approaches within an ecosystem type, location, or situation. Location-specific factors and manager expertise are needed to inform the selection of any strategy or approach.
- Provide an exhaustive set of tactics. We encourage land managers to consider additional actionable tactics appropriate for their projects. Further, not all possible tactics have been vetted through research and so should be employed with caution and followed-up with monitoring and adaptive management.

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How to read this menu

Strategy: A strategy is a broad adaptation response that is applicable across a variety of resources and sites

Approach: An approach is an adaptation response that is more specific to a resource issue or geography

Tactic: Tactics are the most specific adaptation response, providing prescriptive direction about what actions can be applied on the ground, and how, where, and when.

Menu of strategies and approaches

Strategy 1: Maintain or increase extent of forest ecosystems

1.1 Avoid forest conversion to non-forest 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 to 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

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6.2 Increase stocking on well-stocked or understocked forest lands
6.3 Increase harvest frequency or intensity due to 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

Strategy 1: Maintain or increase extent of forest ecosystems

Carbon stocks often reach their highest density in forested ecosystems compared to other ecosystem types or land uses (Liu et al. 2012; Liu et al. 2014). Actions that maintain the integrity of forested ecosystems or re-establish forest cover can have some of the most significant benefits for maintaining carbon in both above- and belowground pools, as well as improving the ability of the ecosystems to sequester carbon into the future. This strategy seeks to sustain or enhance carbon stocks at broad spatial scales through maintaining forest vegetation, increasing forest stocking, or re-establishing forest cover on non-forested lands.

Approach 1.1: Avoid forest conversion to non-forest

Forests are the largest carbon sink in the United States. The high carbon densities of forest ecosystems relative to other terrestrial ecosystems are a result of carbon stocks in both aboveground biomass and significant belowground carbon stored as soil organic matter (Scharlemann et al. 2014). Conversion of forested lands to other non-forest land uses can result in large losses of carbon in both live and dead trees, which comprise about 60% of the carbon in a mature forest (Ryan et al. 2010). Additionally, removal of the canopy can increase decomposition of the litter layer and soil (Noormets et al. 2015), further decreasing carbon pools (Gou and Gifford 2002; Post and Kwan 2000). Conversion of forests to row crop agriculture, pasture, or development represent the largest loss of forests in the United States (McKinley et al. 2011; Puhlick et al. 2017; Thorn et al. 2016).

Examples of adaptation tactics are:

- Designation of conservation easements on forested land
- The use of protective guidelines, such as best management practices, that avoid unintentional loss of forest cover or soil carbon

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- Reducing the amount of forest that is displaced for forest management activities (e.g. designing road systems or landings to minimize their footprint)

Approach 1.2: Reforest lands that have been deforested and afforest suitable lands

Reforestation is the intentional replanting of understocked forestlands (stands in which the growing space is not effectively occupied by crop trees). Here, we also include the establishment of forest vegetation on non-forested lands (also called *afforestation*). Sample et al. (2017) estimate that reforestation of understocked forested lands could result in 13.3 $TgC \cdot yr^{-1}$ (13.3 million metric tons C) of additional carbon stored in aboveground biomass in the U.S, while Hoover and Heath (2011) suggest that 11.3 $TgC \cdot yr^{-1}$ could be sequestered from increased stocking levels in just within the seven states of the northeastern U.S. The contribution of forest soils to this additional carbon sink strength with reforestation is equally significant. Nave et al. (2018) estimate that reforestation could contribute an additional 13-21 $TgC \cdot yr^{-1}$ (13-21 million metric tons C) within forest soils. Carbon sequestration rates can be increased when non-forested lands, such as marginal crop lands, are converted to forests (Ryan et al. 2010; McKinley et al. 2011; Birdsey et al. 2006). For example, nearly half of the carbon sequestered in the U.S. in 2005 came from the regrowth of forests on former crop lands (SOCCR 2007; USEPA 2010), with reported rates of carbon accrual of 0.14–0.34 $MgC \cdot ha^{-1} \cdot yr^{-1}$ (Post and Kwan 2000).

Examples of adaptation tactics are:

- Replanting forests following disturbances that have affected natural regeneration and resulted in understocked stands
- Establishing plantations on marginal croplands or other agricultural lands
- Establishing riparian buffers adjacent to agricultural lands
- Replant forest on land that has been cleared for agriculture, mining, or other reversible uses
- Allow passive regeneration of forest on land that has been cleared for agriculture

Approach 1.3: Increase the extent of forest cover within urban areas

Urban forests include developed sites adjacent to streets and buildings, open spaces in parks, residential areas, and schools, as well as natural areas designated as preserves and large urban parks. Urban forestry can be an important mechanism for increasing stored carbon as trees in urban areas can have significant biomass and carbon sequestration (Nowak et al. 2013). Carbon sequestration rates in individual trees within urban areas can exceed those in natural forests due to greater foliar biomass and reduced competition from lower tree densities, as well as irrigation and fertilization (Jo and McPherson 1995)—and a changing climate may be further accelerating these growth rates in urban areas (O'Brien et al. 2012; Pretzsch et al. 2017). Trees can have an additional important influence on carbon mitigation in urban zones by reducing the energy

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requirements for building heating in winter due to wind protection and summer cooling from tree shading (Nowak et al. 2010).

Examples of adaptation tactics are:

- "Greening" areas that currently have low canopy cover by adding street trees and other vegetation
- Strategic planting of trees to provide building shading or cooling benefits
- Creation of parks and green spaces on abandoned or underutilized spaces, such as brownfields
- Integration of trees as part of low-impact development or stormwater runoff projects

Approach 1.4: Increase or implement agroforestry practices

Landscapes dominated by agriculture often have ecosystems carbon stocks approximately 73-84% lower than forested landscapes due to production systems that are often highly reliant on annual herbaceous crops (Liu et al. 2014). The intentional integration of trees and shrubs into crop and animal production systems has the potential to enhance carbon sequestration and storage from the increase in cover of long-lived woody vegetation. Additionally, agroforestry practices increase the adaptation of agricultural systems to a changing climate through enhancing crop production and protecting soil and water quality (Schoeneberger et al. 2017). Agroforestry practices include (1) silvopasture, (2) alley cropping, (3) forest farming, (4) windbreaks, and (5) riparian forest buffers.

Examples of adaptation tactics are:

- Planting of trees within animal pastures to provide cooling benefits and minimize soil moisture loss
- Production of shade-tolerant crops under a tree canopy
- Establishment of trees and shrubs along field edges and fence lines to reduce soil loss from erosion
- Planting annual row crops between rows of trees to modify microclimates and support crop growth

Strategy 2: Sustain fundamental ecological functions

Many forestry practices work directly and indirectly to maintain the integrity of ecosystems in the face of climate change in order to sustain the functions those systems provide. These land management practices seek to preserve or improve soil nutrient cycling, hydrologic functioning, and vegetation characteristics, and wildlife and insect populations that support productive and healthy forests that store and continue to sequester carbon. This adaptation strategy seeks to sustain or enhance ecological functions to reduce the impacts of a changing climate on forest carbon stocks.

Approach 2.1: Reduce impacts to soils and nutrient cycling

Maintaining both soil quality and nutrient cycling are already common principles of sustainable forest management (Burger et al. 2010; Oliver & Larson 1996) and can help improve the capacity of ecosystems to persist and sustain productivity as environmental conditions change. In addition to maintaining ecosystem productivity, soils are important stores of carbon that are vulnerable to losses from site disturbance due to harvest, recreation, or other natural disturbance (Johnson 1992). Losses of soil carbon are often dependent on soil type, species composition, and soil carbon pool (e.g., forest floor, mineral soil; Nave et al. 2010), although soil carbon pools typically recover given enough time (Hoover 2011). Greater intensity of harvest removal or soil disturbance can result in greater soil carbon loss and long-term impacts on forest carbon stocks (Achat et al. 2015; Bucholz et al. 2013). Additionally, disturbance can cause physical and chemical changes to soils, including soil compaction, mixing of soil layers, erosion, and removal of organic layers. These impacts can significantly alter soil biotic communities with consequences for nutrient cycling, including the leaching or fixation of nutrients that can affect the ability of ecosystems to sequester carbon. Many existing guidelines for reducing impacts to soils and nutrient cycling are likely to be beneficial, either in their current form or with modifications, for maintaining existing carbon stocks and sequestration capacity with increasing forest stressors from climate change.

Examples of adaptation tactics are:

- Altering the timing of forest operations to reduce potential impacts on water, soils, and residual trees, especially in areas that rely on particular conditions for operations that may be affected by a changing climate
- Retaining coarse woody debris (e.g., tree tops, harvest residue) to maintain soil moisture, nutrients, and enhance soil organic matter pools
- Using soil amendments to restore or improve soil quality
- Restoring native herbaceous groundcover following management activities in order to retain soil moisture and reduce erosion

Approach 2.2: Maintain or restore hydrology

Carbon cycling in forests is strongly dependent on the abundance and movement of water within forest ecosystems ; adequate soil moisture is necessary for maintaining growth and productivity of forests, while trees help regulate rainfall by recharging atmospheric moisture through

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transpiration and regulating soil moisture through cooling the ground surface and enhancing soil infiltration (Ellison et al. 2017). Projected changes in precipitation and temperature are expected to alter hydrologic regimes through changes in streamflow, snowpack, evapotranspiration, soil moisture, infiltration, flooding, and drought. In addition to a changing climate, hydrology can be altered by infrastructure (e.g., dams, roads, and other impervious surfaces), groundwater extraction, stream channelization, or invasive plants. Some ecosystems many be susceptible to carbon loss from drought stress, from either direct effects on vegetation or indirect impacts, such as reduced tree resistance to pest attacks (Rouault et al. 2006). Other ecosystems may be susceptible to carbon losses from damage due to flooding, ponding, or soil losses from erosion. It is important to keep in mind that modifications to maintain hydrology at one site may have negative impacts on hydrology at another site.

Examples of adaptation tactics are:

- Reducing or eliminating agricultural drainage improvements near wetlands
- Reducing groundwater withdrawals in groundwater recharge areas
- Installing berms or dikes to divert surface water to areas affected by decreased precipitation
- Removing or temporarily closing access roads to reduce soil erosion and sedimentation
- Redesign infrastructure to accommodate greater hydrologic extremes in the future

Approach 2.3: Prevent the introduction or establishment of invasive plant species or remove existing invasive species

Nonnative invasive plant species represent a major challenge for land managers, which are expected to intensify into the future as climate change increases habitat for many invasive species, and global trade expansion, agriculture, and other human activities introduce new nonnative species. Nonnative invasive species impact many ecosystem processes critical for carbon cycling in forests, including nutrient cycling (Liao et al. 2008), hydrology (Gordon 1998), and regeneration of native herbaceous and tree species (Aronson and Handel 2011). Current methods for controlling nonnative invasive species emphasize early detection and rapid response to new infestations (Hellman et al. 2008). Over the long term, limitations in available resources may require managers to prioritize which species to eradicate and which to allow to occupy sites based on expected or observed impacts to desired ecosystem functions.

Examples of adaptation tactics are:

- Cleaning equipment prior to forest operations in order to prevent the spread of invasive plants during site preparation, harvesting, or other activities
- Maintaining closed canopy conditions to reduce the ability of light-loving invasive species to enter the understory

- Increasing monitoring efforts for known or potential invasive species to ensure early detection, especially at trailheads, along roads, and other areas known for infestation

Approach 2.4: Maintain or improve the ability of forests to resist pests and pathogens

Insect pests and pathogens affect large areas of forest across the U.S. annually. Although impacts are typically diffusely distributed across forest ecosystems, damage from insects and pathogens can cause large-scale transformations of forests through changes to species composition, forest productivity, and carbon stocks (Clark et al. 2009; Williams et al. 2016). Approximately 6% of forests are at risk to lose at least 25% live basal area in the next 15 years from insects and pathogens (Krist et al. 2007), with an estimated reduction of 21 TgC yr^{-1} in live biomass (Williams et al. 2016). Climate change has the potential to add to or intensify the impact of insect pests and forest pathogens, particularly where site conditions may increase the susceptibility of forests to damage (Spittlehouse & Stewart 2003). Management actions that alter the density, structure, or species composition may reduce the vulnerability of forest stands to carbon losses from these agents.

Example adaptation tactics are:

- Thinning to reduce density of a host species to reduce infestation
- Increasing diversity of tree species within forest stands
- Creating a diversity of age classes or stand structures to reduce the availability of preferred hosts for pests and pathogens
- Using pesticides or biological control methods to manage pest populations in infested areas

Approach 2.5: Reduce competition for moisture, nutrients, and light

Competition for resources between plants is a primary mechanism in plant succession and evolution (Weiner 1990). Plants compete aboveground for light and belowground for water and nutrients, such as nitrogen and phosphorus (Casper and Jackson 1997). A changing climate is expected to alter competitive relationships in forest ecosystems as growing seasons become longer, carbon dioxide (CO_2) levels increase, precipitation patterns change, and temperatures increase. Reducing competition for limiting resources for desired tree species, particularly for seedlings and saplings, will increase the ability of forest systems to cope with the direct effects (moisture stress, increased temperatures) and indirect stress (increased pressure from pests and pathogens) of climate change (Evans and Perschel 2009). Reducing competition by alleviating climatic and biological stressors for desired species at early stages of recovery from disturbance can accelerate structural development in forest ecosystems (Dwyer et al. 2010) and increase carbon sequestration both during and following drought (Bottero et al. 2017).

Examples of adaptation tactics are:

- Using herbicide or mechanical treatments to remove undesired species including invasive nonnative or aggressive native species
- Proper spacing of trees during post-disturbance planting activities
- Prevention of undesirable or invasive species
- Using prescribed fire to maintain conditions favorable to fire-tolerant species
- Chipping woody debris to accelerate decomposition and soil nutrient availability

Strategy 3: Reduce carbon losses through decreased natural disturbance, including wildfire.

Natural disturbance events—including insect pests and diseases, damage from wind and ice, drought, and wildfire—typically reduce near-term forest carbon stocks while initiating long-term and gradual recovery. These disturbances are both a major causes of carbon loss in forests (Williams et al. 2016) and influence future sequestration rates through impacts on species composition, ecosystem structure, rates of photosynthesis and respiration, and flows through various carbon pools (Noormets et al. 2015). While forest regrowth offsets carbon losses following human and natural disturbances over time allowing U.S. forests to remain a net carbon sink (Pan et al. 2011), enhanced disturbance frequency, severity, or extent from climate change may enhance large-scale forest carbon release (Peterson et al. 2014). Shifting climatic conditions, including earlier snowmelt, low precipitation, and warmer temperatures contribute to increases in fire size, frequency, and the area burned annually in the U.S. (Littell et al. 2009; Westerling et al. 2006). Impacts of wildfire on forest carbon sequestration can be long lasting and profound, particularly when they occur outside of the historical fire regime. Not only do wildland fires emit carbon stored in trees that have been burned, but mineral soils and forest floor carbon stocks can also be reduced significantly (Nave et al. 2011; Pellegrini et al. 2018). Additionally, carbon sequestration rates can be lowered in burned areas because of negative impacts on vegetation productivity following severe fire (Hicke et al. 2013). While many actions associated with this strategy can result in a short-term, low magnitude, or fine-scale forest carbon loss, this strategy aims to avoid or reduce long-term, large magnitude, or broad-scale carbon losses through management actions intended to decrease natural disturbance frequency, extent, intensity, or severity.

Approach 3.1: Restore or maintain fire in fire-adapted ecosystems

Wildfires are a major contributor of U.S. forest carbon emissions, although annual emissions can vary greatly from year-to-year (Wiedinmyer and Neff 2007). Prescribed fire can reduce fuel loads, significantly reducing the risk of uncontrolled fire or shifting fire regimes from infrequent, high severity fires towards more frequent, low severity fires (Miller et al. 2009) that result in lower carbon emissions compared to wildfire (Agee et al. 2005). Additionally, prescribed fires limit the extent of wildfire if one were to occur (Boer et al. 2009). Conditions during implementation of prescribed fire typically result in low overstory tree mortality rates, preserving both carbon in live trees and the potential to sequester future carbon through tree growth (Tian et al. 2008).

Examples of adaptation tactics are:

- Using prescribed fire to reduce ladder fuels, invasive species, and understory competition
- Promoting fire- and drought-tolerant species and ecosystems in areas expected to have increased fire risk
- Using natural or prescribed fire to restore the open character within woodlands and glades
- Shifting the prescribed burning season to align with seasonal precipitation changes or altered fire weather to reduce risk of unintended fire conditions

Approach 3.2: Establish natural or artificial fuel breaks to slow the spread of catastrophic fire

Increased warming and drying driven by climate change has increased fire-season fuel aridity to accelerate forest fire activity in many parts of the U.S. (Abatzoglou & Williams 2016; Westerling et al. 2006). Under these conditions, wildfire can expand quickly affecting large areas in a short duration of time. Establishing fuel breaks can constrain fire spread or reduce fire intensity by reducing flame lengths, which may enhance fire suppression efforts and limit the extent of carbon losses during wildfire. Establishing fuel breaks are often complimentary to management actions that reduce fuel loads (Agee et al. 2000).

Examples of adaptation tactics are:

- Mowing fuel breaks adjacent to roadways to prevent establishment of fire from vehicle traffic
- Mechanical thinning of fire-prone vegetation in strips
- Creating fire lines, where vegetation is removed down to mineral soil, in areas of high fire risk
- Strategic establishment of fire-resistant vegetation to limit the establishment, rate of spread, or intensity of wildfire

Approach 3.3: Alter forest structure or composition to reduce the risk or severity of wildfire

Forest structure and composition may increase the risk of wildfire, particularly with changing patterns of precipitation, increased temperatures, and longer growing seasons. Management actions that decrease risk of wildfire by altering forest structure or species composition can reduce risk of wildfire or fire severity. Reducing the severity of fires from fuel reduction

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treatments can have benefits from lowered carbon emissions from fires when they do occur due to reduced fuel consumption (Mitchell et al. 2009). Additionally, decreased fire severity may lower the negative impacts on tree mortality, regeneration, or creation of hydrophobic soil conditions that can have long-lasting effects on forest productivity and forest carbon recovery (Carlson et al. 2012).

Example of adaptation tactics are:

- Promoting fire-resistant species, such as hardwoods, in buffer zones between conifers to slow the movement of wildfire
- Removing dead or dying trees or other vegetation to reduce surface and ladder fuels
- Thinning to reduce tree density in fire-prone ecosystems
- Reducing fuel loading and maintaining open conditions in ecosystems at lower elevations to reduce risk of fire spread upslope
- Increasing height to live crown to create forest structure that is expected to be less vulnerable to severe wildfire

Approach 3.4: Reduce the risk of tree mortality from biological or climatic stressors in fire-prone systems

The complex interactions and feedbacks between climate, vegetation, and tree insect pests on fire occurrence and behavior have global consequences for atmospheric carbon concentrations (Sommers et al. 2014). Extensive tree mortality due to drought, insect pests and pathogens, weather extremes, or other climate-related disturbances greatly increases fuel loads and the risk of wildfire. Fire risk may respond over short timeframes if vegetation mortality occurs quickly, such as when windthrow occurs, or have a time-lagged response due to interactions between multiple stressors (Reichstein et al. 2013). Management actions that reduce susceptibility of forest stands to drought-, insect-, or disturbance-induced tree die-offs may reduce susceptibility to these threats.

Example of adaptation tactics are:

- Thinning forest stands to reduce risk of drought-induced mortality
- Selective harvest to lower the density of a host species for a pathogen or insect pest
- Increasing diversity of tree species within forest stands
- Diversifying age classes or stand structures to reduce the impacts of pests and pathogens
- Reducing susceptibility to drought and windthrow with by thinning stands when young

Approach 3.5: Alter forest structure to reduce severity or extent of wind and ice damage

Wind disturbance from microbursts, tornadoes, hurricanes, or other high wind events is a fundamental natural disturbance process that contributes to tree mortality in many forest ecosystems (Dale et al. 2001). Damage from wind events is estimated to be one of the most prominent disturbances in the Midwest and Northeast (Boose et al. 2001; Frehlich 2002; Seymour et al. 2002). A warming atmosphere is driving more frequent and intense storms, including hurricanes and thunderstorms with high winds (USGCRP 2017) that may be contributing to greater transfers of carbon from live to dead forest carbon pools (Williams et al. 2016). Interactions between severe wind events and altered temperature and precipitation patterns may further increase windthrow occurrence in some forests due to impacts on tree anchorage and wind exposure (Seidl et al. 2017). Similarly, ice storms have important consequences for carbon dynamics in forests systems from loss of productivity from leaf area losses, crown loss from stem breakage, or damage to stems that increases susceptibility to insects and disease (Dale et al. 2001). Management actions that alter the structure or species composition may reduce the vulnerability of forest stands to carbon losses from these agents.

Example adaptation tactics are:

- Retaining trees at the edge of a clearcut or surrounding desirable residual trees to help protect trees that have not been previously exposed to wind
- Conducting forest harvest over multiple entries in order to gradually increase the resistance of residual trees to wind
- Using directional felling, cut-to-length logging, and other harvest techniques that minimize damage to residual trees
- Favoring species that are less susceptible to wind or ice damage, such as sugar maple and red or white oak
- Removal of trees in poor health or showing poor form that increase susceptibility to wind or ice damage

Strategy 4: Enhance forest recovery following disturbance

Ecosystems may face significant impacts as a result of climate-related alterations in disturbances, including fire, invasive species, and severe weather events (Dale et al. 2001; Seidl et al. 2017). Although disturbances are primary drivers of many ecosystems, changes in disturbance frequency, severity, extent, or duration may have important implications for the carbon balance of many forest ecosystems (Williams et al. 2016). Although many disturbances are not possible to predict, land managers can increase the preparedness of ecosystems for large and severe disturbance and prioritize rapid response to mitigate impacts on carbon. Adequate planning in advance of disturbance may facilitate earlier or more flexible response and prevent maladaptive responses that reduce or delay carbon recovery rates. This strategy involves consideration of various approaches that enhance the recovery of ecosystems, augmenting the ability of plant communities to initiate carbon sequestration quickly following disturbance.

Approach 4.1: Promptly revegetate sites following disturbance

Disturbances typically result in the immediate loss of existing carbon stocks in live biomass and the transfer of carbon from live to dead forest carbon pools with eventual loss as decomposition. Large and severe disturbances may additionally cause decreased carbon sequestration capacity from disrupted regeneration and reduced forest productivity in the long term, as well as carbon loss from soil erosion. Prompt revegetation of sites following disturbance can reduce carbon losses from soil erosion, quickly enhance carbon gains through tree growth, and provide opportunities to promote natural regeneration or foster species that may be better adapted to future conditions (Thom et al. 2017).

Example adaptation tactics are:

- Seeding disturbed sites with quickly establishing (herbaceous, sub-shrub, and shrub) species following disturbance to stabilize soils
- Planting tree species expected to be adapted to future conditions and resistant to insects pests or present pathogens
- Creating suitable conditions for natural regeneration through site preparation
- Planting larger individuals (saplings versus seedlings, or containerized versus bare-roots stock) to help increase survival

Approach 4.2: Restore disturbed sites with a diversity of species that are adapted to future conditions

Many native species are expected to be well adapted to the future range of climatic and site conditions (Prasad et al. 2018). Using management actions that favor such native species in community or forest types can facilitate a shift towards a composition that supports increased forest productivity and enhanced sequestration capacity. Novel mixes of native species that may not have historically occurred in forest or community types may allow for maintaining or enhancing productivity and carbon sequestration as climatic and site conditions change into the future. Unique combinations of native species may lead to altered competitive relationships and result in the conversion to newly defined community types (Davis et al. 2005; Root et al. 2003).

Example adaptation tactics are:

- Planting native species on a site to increase overall species richness and provide more options for future management
- Favoring or establishing drought- or heat-tolerant species (*e.g.* pine or oak species) on south-facing slopes, sites with sandy or shallow soils, or narrow ridgetops.

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- Site preparation to promote the establishment of oak from an adjacent site
- Allowing a species native to the region to establish where it was not historically present, if it is likely to do well there under future climate conditions

Approach 4.3: Protect future-adapted seedlings and saplings

As climate change increases direct and indirect stressors on forest ecosystems, it becomes increasingly important to ensure adequate regeneration of tree species following disturbance-induced canopy cover loss in order to recover forest productivity and carbon sequestration capacity. Seedlings and saplings are generally more sensitive than older growth stages to changes in temperature, soil moisture, herbivory, physical disturbance, and other stressors (Walck et al. 2011). Protection of seedlings or saplings of existing or newly migrated species can strongly shape ways in which communities adapt (TNC 2009) and lead to increased biomass and ecosystem carbon stocks into the future (Duvenck & Scheller 2015; Hof et al. 2017).

Examples of adaptation tactics are:

- Using repellant sprays, bud caps, or fencing to prevent browsing on species that are expected to be well adapted to future conditions
- Using tree tops from forest harvest to protect regeneration from browse pressure
- Restricting recreation or management activities that may have the potential to damage regeneration
- Protecting advanced regeneration from damage during timber harvest activities
- Partnering with state wildlife agencies to monitor herbivore populations or reduce populations to appropriate levels

Approach 4.4: Guide changes in species composition at early stages of development to meet expected future conditions

Disturbances often initiate regeneration which can be an opportunity to facilitate adaptation through ecosystem reorganization. Such guided changes reduce the disequilibrium between species composition and climatic conditions (Joyce et al. 2009; Thom et al. 2017). When prominent species within an ecosystem are projected to decline as climate changes, management actions are needed that adjust species composition following disturbance to better align with the range of expected future conditions. These actions may result in enhanced carbon sequestration compared to relying on unaided successional processes.

Examples of adaptation tactics are:

- Promoting regeneration of species currently present that have wide ecological amplitude and can persist under a wide variety of climate and site conditions

- Planting species expected to be adapted to future conditions, especially where natural regeneration following disturbance is widely failing
- Site preparation that favors natural regeneration of future-adapted species
- Allowing nonnative or aggressive native species to remain as part of a novel mix of species, rather than eradicating these species (recognizing the potential invasion risk)

Strategy 5: Prioritize management of locations that provide high carbon value across the landscape

Ecosystem carbon density varies spatially across forest and community types due to many factors, such as differences in topography, hydrology, soils, stand age, and disturbance and management history and how these elements influence plant community composition and carbon flux processes (Luyssaert et al. 2007). Sites may have high carbon stock densities from either enhanced carbon inputs or conditions that reduce the loss of carbon. High carbon inputs to a site can result from greater productivity of vegetation, high densities of aboveground biomass, or translocation of carbon from adjacent sites, such as soil deposition in floodplains (Behre et al. 2007). Additionally, sites may have high carbon densities from reduced carbon losses, such as hydrologic conditions that result in saturated soil conditions limited decomposition and that cause the formation of organic soils. When managing forest ecosystems for carbon, identifying sites containing high carbon densities may be a priority for management in order to retain existing forest carbon stocks. A changing climate is expected to impact sites important for carbon stocks in different ways, depending on vulnerability of the carbon stocks or flux processes to climatic or biological stressors that are expected to intensify.

Approach 5.1: Prioritize low vulnerability sites for maintaining or enhancing carbon stocks

Tree mortality from drought, pests and pathogens, fire, windthrow, or other natural disturbances are important causes of carbon loss across forest ecosystems. Sites with characteristics that reduce disturbance frequency or severity, or lower the vulnerability to carbon loss when these disturbances occur, may provide high value for maintaining or enhancing carbon stocks as climatic and biological stressors intensify. Characteristics that lower vulnerability to carbon loss from disturbance may include: (1) high canopy cover or advanced regeneration of species with wide temperature or moisture tolerances (Duveneck and Scheller 2015; Hof et al. 2017, (2) site hydrology or soil fertility that reduces drought or nutrient limitation impacts to forest productivity (Ellison et al. 2017), or (3) enhanced species or structural diversity that may lower vulnerability or enhance recovery from impacts from pests or pathogens (Spies et al. 2010). Maintaining higher carbon stocks on sites with these characteristics that impart greater resistance or resilience to disturbance may provide greater benefit from carbon storage at landscape scales (Rosoman et al. 2017), similar to how sites resistant to climate stressors may provide the best chance for retaining habitat for at-risk species (Anderson et al. 2012). Additionally, sites may be prioritized for management actions that augment existing characteristics important for resistance to carbon loss or resilience for regaining carbon when disturbances do occur.

Examples of adaptation tactics are:

- Increase retention of large diameter trees on sites with low vulnerability to drought stress
- Enhancement of species or structural diversity in high carbon stock sites
- Prioritize large, unfragmented forest patches, or sites that otherwise minimize exposure to stressors that could increase tree mortality of carbon losses
- Promote old forest conditions by limiting harvest removal
- Increase redundancy of important sites for existing carbon stocks across the landscape

Approach 5.2: Establish reserves on sites with high carbon density

Areas with exceptionally high densities of carbon may warrant protection through the establishment of reserves (Duveneck and Scheller 2016; Man et al. 2013). Reserves are traditionally defined as natural areas with little to no harvest activity that do not exclude management of fire or other natural disturbance processes (Halpin 1997). However, the impacts of climate change on forest carbon dynamics may necessitate an adjustment of the use and definition of reserves, such that it may be valuable to retain flexibility in the use of management practices that support the maintenance of high carbon stocks.

Examples of tactics are:

- Setting a minimum requirement for percentage or area of land in reserves
- Identifying areas with high belowground carbon stocks that may be sensitive to disturbance, such as wetland or other organic soils
- Expanding the boundaries of reserves to core size
- Designation of buffer zones of low-intensity management around core reserve areas
- Restoring or increasing the occurrence of sites with community types with high carbon value

Strategy 6: Maintain or enhance existing carbon stocks while retaining existing forest character

Climate change is projected to increase the potential for severe disturbance events that reduce forest ecosystems carbon stocks (Williams et al. 2016), while additionally affecting the growth and regeneration of extant species. Many forest management decisions aim to limit the negative impacts of disturbances while enhancing the growth of residual trees and the regeneration of desired species that represent the current and future capacity of the ecosystem to sequester carbon (McKinley et al. 2011). Often these management actions aim to enhance existing forest conditions, such as species composition and stand structural diversity that are key to the desired services provided by the forest. Slight adjustments in forest conditions can improve the retention of carbon within various forest carbon pools or enhance the rate of recovery following a disturbance event without dramatically altering the character of forest ecosystems.

Approach 6.1: Increase structural complexity through retention of biological legacies in living and dead wood

Late-successional and old-growth forests store more carbon compared to young or secondary forests, such that stand age is often a reliable predictor of carbon stocks for a given forest type (Keeton et al. 2007; Gray et al. 2016). Older forests typically have greater structural complexity, including higher density of carbon stocks in both live and dead trees (Franklin et al. 2002; McGarvey et al. 2015). Particularly in temperate deciduous forests, moderate severity disturbance in late-successional and old-growth forests transfers carbon from live to dead pools that increases carbon storage. The greater structural complexity that results from this moderate severity disturbance increases resource-use efficiency and resource availability to maintain greater levels of carbon sequestration rates than previously thought (Curtis and Gough 2018). Silvicultural practices that increase structural complexity through maintaining older or larger-diameter legacy trees and greater amounts of dead wood including snags, down logs, and coarse woody debris may increase carbon storage (D'Amato et al. 2011; Ford and Keeton 2017; Mika and Keeton 2015; Palik et al. 2014). Coarse woody debris may contribute to enhanced soil carbon stocks and nutrient pools (Wiebe et al. 2014), directly contributing to carbon storage in mineral soils as well as influencing forest carbon sequestration into the future (Magnusson et al. 2016). Downed logs and coarse woody debris can serve as nurse logs or provide microclimates important for seed germination or seedling establishment, which may play an important role for a species' persistence or colonization of new habitat as environmental conditions change (Gunn et al. 2009).

Examples of adaptation tactics are:

- Retaining the oldest and largest trees with good vigor during forest management activities
- Retaining survivors of pest and disease outbreaks, droughts, windthrow events, or other disturbances during salvage operations
- Retaining down logs, snags, and other dead wood during forest management, or leaving trees of poor health that are expected to contribute to dead wood pools
- Not salvage logging where risks from fire or to forest health are low

Approach 6.2: Increase stocking on well-stocked or understocked forest lands

When risk of carbon loss from natural disturbance is low, maintaining greater carbon stocks in live tree biomass can provide significant carbon benefits over long periods of time (Galik and Jackson 2009). In uneven-aged systems, greater carbon stocks can be achieved through increased duration of time between harvest entry (D'Amato et al. 2011) greater rates of retention when harvest does occur (Duveneck et al. 2014; Hoover and Stout 2007; Nunery and Keeton 2010; Puhlick et al. 2016; Russell-Roy et al. 2014). In a modeling study conducted in the Upper Midwest region, increasing retention of live tree biomass during harvest increased total forest carbon stocks in hardwood and conifer stands by 25% and 37%, respectively (Peckham et al. 2013). Additionally, greater carbon stocks can be maintained in even-aged systems from increasing rotation lengths (Duveneck and Scheller 2016; Mika and Keeton 2015; Law et al. 2018). For example, increasing rotation ages 15 years in softwood stands in New England could sequester an additional 0.82 MgC ha^{-1} yr^{-1} (Perschel et al. 2007), while extending rotations on private lands in Oregon from 45 to 80 years would increase state-level carbon stocks by 17% (Law et al. 2018).

Increasing stand stocking levels on understocked forestlands (land with >10% cover of live trees) that are considered understocked (<60% of fully stocked) has the potential to increase carbon density in live biomass carbon pools. For example, Hoover and Heath (2011) estimate ~49% of timberland in the Northeast is understocked, with the potential to store an additional 454 TgC over 40 years if fully stocked. Land managers can improve forest productivity and the amount of carbon stored within forests by managing the stand density (e.g., basal area, or trees per hectare) and species composition, often in comparison to a reference stand of similar age and productivity potential that is considered fully stocked. The benefits of increasing stand stocking levels, however, may need to be compared to the increased risk of carbon loss from disturbance (e.g., from wildfire or drought-induced tree mortality) resulting from increased tree densities. Stands where vulnerability to carbon losses is determined to be low may provide additional carbon benefits from increasing stocking rates.

Examples of adaptation tactics are:

- Underplanting, especially planting species with wide temperature and moisture tolerances, or species underrepresented in current stand inventory
- Harvesting poorly-stocked stands of low productivity to initiate regeneration and increase stocking levels
- Lengthening rotations on highly productive sites
- Silvicultural prescriptions that increasing structural retention, such as selection cutting, shelterwood, or other low-intensity harvest methods
- Retention of larger diameter-class trees

Approach 6.3: Increase harvest frequency or intensity due to greater risk of tree mortality

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Decreasing carbon stocks may provide carbon benefits in scenarios where risk of carbon loss from disturbance is high. A changing climate may increase the frequency or magnitude of disturbances such as drought, fire, or insect damage he can result in widespread or high rates of tree mortality. A reduction in stand-level carbon stocks may decrease risks of carbon losses where stand conditions increase the vulnerability to disturbance-related mortality. Shortening rotation lengths in even-aged stands may provide the greatest long-term carbon benefit by maintaining moderate levels of ecosystem carbon stocks while minimizing the risk of large carbon losses if disturbance does occur (Galik and Jackson 2009). For example, projected growth declines from water limitations in managed boreal jack pine (*Pinus banksiana*) forests could result in greater carbon sequestration from a reducing rotation length from 79-80 years to 50 years (Wang et al 2013). Shortening rotation lengths have additionally been shown to benefit aboveground biomass in stands with an increased risks of carbon loss to fire (González et al. 2005) or ice storms (Irland 2000). Shortening rotation lengths may also provide increased opportunities for harvesting wood products and transitioning the system to a species composition better adapted to future conditions, increasing overall forest carbon over long time periods. Likewise, shortening rotations increases the number of generations with the potential to increase the genetic adaptation of a species in future climate conditions (Duveneck and Scheller 2016). In cases of shortening rotations of maladapted species, prompt reforestation should occur in order to quickly initiate carbon sequestration (Swift 2012). Likewise, if risk of disturbance is high, practices that decrease carbon stocks through reductions in stand densities (e.g., thinning) may lower the vulnerability to carbon losses from drought while increasing carbon sequestration rates through improved residual stand growth (Bottero et al. 2017; D'Amato et al. 2013) and understory carbon stocks (Zhou et al. 2013), potentially without decreasing stand-level carbon stocks over longer time frames (Powers et al. 2012). Additionally, reducing stand densities can decrease susceptibility to damage from wind and ice storms (Balch 2014).

Examples of adaptation tactics are:

- Thinning even-aged stands to reduce competition for limiting soil moisture on drought-prone sites
- Decreasing rotation length of even-aged stands in disturbance-prone systems
- Reducing stand densities in sites susceptible to southern pine beetle infestation
- Increasing tree spacing between co-dominant trees to reduce susceptibility to wind and ice damage

Approach 6.4: Disfavor species that are distinctly maladapted

A species is considered maladapted when its environment changes at a rate beyond the species' ability to adapt and accommodate those changes (Johnston 2009). Species at the southern or highest elevational extent of their geographic range are vulnerable to habitat loss with projected changes in climate (Iverson et al. 2008), making forest stands with a high proportion of live carbon stocks as maladapted species more vulnerable to carbon loss as environmental conditions change (Duveneck et al. 2014; Duveneck & Scheller 2015). Species declines may require rapid and aggressive management responses to maintain forest cover and carbon sequestration capacity. In ecosystems where the dominant species are likely to decline substantially, this may mean dramatically altering the species assemblage through active or passive means.

Examples of adaptation tactics are:

- Removing unhealthy individuals of a declining species in order to promote other species expected to fare better
- Retaining healthy trees to promote complexity and augment habitat, while retaining some carbon on site
- Protecting healthy legacy trees that fail to regenerate while deemphasizing their importance in the mix of species being promoted for regeneration

Approach 6.5: Manage for species and genotypes with wide moisture and temperature tolerances

Inherent scientific uncertainty surrounds climate projections at finer spatial scales, making it necessary to base decisions upon a wide range of predictions of future climate (Brandt et al. 2017). Although projections of future climate differ across regions, models generally highlight increasing average annual temperatures, along with varying impacts on precipitation (USGCRP 2017). Rising temperatures along with greater variation in precipitation patterns has increased the year-to-year variability in growing season soil moisture conditions for some regions in the US (Hubbart et al. 2016; Easterling et al. 2017). This increased climate variance, which can result in conditions of both drought and excessive wetness across short time periods, has important consequences for potential declines in forest health that negatively impact productivity and carbon sequestration (Hubbart et al. 2016; Kutta and Hubbart 2018). Forest management actions that favor a variety of species and genotypes with a wide range of moisture and temperature tolerances may better distribute risk than attempting to select species with a narrow range of tolerances that are best adapted to a specific set of future climate conditions (The Nature Conservancy 2009). Diversifying forest composition to include species with wider climatic tolerances can increase the capacity of forest stands to sequester carbon in the future as conditions change (Duveneck and Scheller 2015; Hof et al. 2017). Likewise, even-aged forest stands that reach the economic optimum of the rotation age that transition to alternative species with wider environmental tolerances can maintain or increase profitability and carbon sequestration rates (Susaeta et al. 2014).

Examples of adaptation tactics are:

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- Favoring species that are currently present that have wide ecological amplitude and can persist under a wide variety of climate and site conditions
- Planting or otherwise promoting species that have a large geographic range, occupy a diversity of site locations, and are projected to have increases in suitable habitat and productivity
- Promoting long-lived species with wide ecological tolerances

Approach 6.6: Promote species and structural diversity to enhance carbon capture and storage efficiency

Species are vulnerable to stressors at different stages of their life cycle, such that even-aged stands are often more vulnerable to disturbances such as insect pests and disease. Likewise, greater compositional diversity may reduce vulnerability to disturbances. As one or more species are at risk for a given stressor, greater diversity reduces the likelihood that the entire systems will decline (Duveneck et al. 2014). Even as greater species and structural diversity confer reduced vulnerability to carbon losses from disturbance, particularly under a changing climate (see review by O'Hara and Ramage 2013), these characteristics can also increase carbon density in forest ecosystems. Higher rates of carbon storage and annual carbon sequestration can result from resource-use efficiencies from increased diversity of tree species (Ammer 2018; Curtis and Gough 2018; Lui et al. 2018; Ruiz-Benito et al. 2014; van der Sande et al. 2017), while increased carbon stocks can be supported with a greater diversity of age classes and more vertical and horizontal structural complexity (Gunn et al. 2014; Ford and Keeton 2017; McGarvey et al. 2015). Results from both modeling and experimental studies suggest that over longer time scales (*e.g.* 50-100 years) silvicultural practices that promote uneven-aged management in forests promote greater carbon stocks in forests (D'Amato et al. 2011; Duveneck and Scheller 2015; Li et al. 2007; Mika and Keeton 2015). Carbon stocks in forests managed for increased structural and species diversity may increase over long temporal scales despite short-term reductions in carbon.

Examples of adaptation tactics are:

- Forest management practices that emulate aspects of disturbance, such as variable density treatments
- Smaller, more frequent management interventions to encourage the development of multiple age cohorts or greater species diversity
- Silvicultural treatments that encourage diverse regeneration of native species, such as larger patch cuts
- Using salvage methods that create desired residual stand structures following disturbance

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Approach 6.7: Use seeds, germplasm, and other genetic material from across a greater geographic range

Planted stock often exhibits greater survival when originating from local seed sources, but changing environmental conditions may eventually result in poor establishment or survival of seedlings derived from local sources (Vitt et al. 2010) that can result in understocked forests with lower rates of carbon sequestration. Using seed zones that reflect regional analyses of projected changes in environmental conditions over time may provide seed sources better suited to conditions than static seed zones (Erickson and Navarrete-Tindall 2004, Millar et al. 2007, Spittlehouse and Stewart 2003). This may entail importing genetic stock from a variety of locations, ranging from local sources to stock originating beyond its current range in order to provide material that are likely to be better suited to the current or future climate that enhances future forest carbon stocks. Although using this strategy requires moving species or genotypes to new habitats or locations, this strategy is intended to maintain forest functioning including carbon sequestration capacity (Duveneck et al. 2014; Duveneck and Scheller 2015), and may require communicating with policy-makers to reevaluate seed zone sizes and rules governing the movement of seed. It is important to note that although many environmental factors may match seedlings to geographic areas, limitations such as cold tolerance may remain (Millar et al. 2007). It is also important to take the necessary precautions to avoid introducing a new invasive species (Vitt et al. 2010).

Examples of adaptation tactics are:

- Using mapping programs to match seeds collected from a known origin to planting sites based on climatic information to maximize carbon sequestration potential
- Identifying and communicating needs for new or different genetic material to seed suppliers or nurseries to increase diversity of available stock
- Planting seedlings germinated from seeds collected from various locations throughout a species' native range

Strategy 7: Enhance or maintain sequestration capacity through significant forest alterations

Land managers already work in many ways to increase forest productivity through enhancing structural heterogeneity and species diversity (Franklin et al. 2007). As an adaptation strategy for managing forest carbon, this general goal receives added effort and focus when managing systems whose current characteristics limit the ability of the forest to sequester carbon or increase the risk of carbon losses through disturbance under a changing climate (Fahey et al. 2018; Nagel et al. 2017). This strategy is focuses on altering the characteristics of a forest through intentional alterations of species composition and structure so the desired future conditions of the forest are significantly changed from current conditions (Millar et al. 2007; Swanston et al.

2016). These changes may be necessary in order to create ecosystems that are better adapted to the range of expected future conditions, thereby maintaining desired ecosystem services, including carbon sequestration and storage and reducing the risk of carbon loss from disturbance.

Approach 7.1: Favor existing species or genotypes that are better adapted to future conditions

Large reductions in carbon can occur with some natural disturbances and can result in species composition changes. Favoring or restoring species expected to be well adapted to future climate through management practices can facilitate a gradual shift in the forest composition that allows for continued levels of forest carbon stocks without disturbance-related carbon reductions (Thom et al. 2017). For a particular site or forest type, there are likely many species that may be well adapted to the future range of climatic conditions (Landscape Change Research Group 2014, Walk et al. 2011). Some future-adapted tree species may be present at a particular site as a minor component of the community. Management actions that emphasize or restore these future-adapted species now may create opportunities to increase their relative abundance to fill the niche left by maladapted species that decline. Where communities are dominated by one or a few species, this approach will probably lead to conversion to a different community type, albeit with native species.

Examples of adaptation tactics are:

- Underplanting a variety of native species on a site to increase overall species richness and provide more options for future carbon sequestration capacity
- Favoring or establishing oak, pine, and other more drought- and heat-tolerant species on narrow ridge tops, south-facing slopes with shallow soils, or other sites that are expected to become warmer and drier to reduce potential carbon losses in the future as temperatures increase and precipitation patterns change
- Seeding or planting drought-resistant genotypes of productive commercial species (e.g., loblolly pine) where increased drought stress is expected.

Approach 7.2: Alter forest composition or structure to maximize carbon stocks

Structural and species diversity may buffer a community against the susceptibility of its individual components to climate change (Peterson et al. 1998). Biodiverse and multi-aged forest stands store more carbon relative to even-aged stands (Ammer 2018; Keeton et al. 2011) and can exhibit both resistance to disturbance-induced carbon loss and resilience when disturbances do occur, more quickly recovering carbon stocks over time (Duvenck and Scheller 2016; O'Hara and Ramage 2013). Substantially altering forest stand characteristics, including the creation of a greater mix of tree species, ages, size classes, and canopy complexity can improve the ability of forest stands to capture carbon through improved productivity, and well as reduce the risk of carbon loss (Ford and Keeton 2107). This may include introducing new species not currently found within existing forest communities, including moving species into new regions (*e.g.* assisted migration). While these actions may reduce the future disequilibrium between climate and a species' traits, movement of species to new locations remains a challenging and contentious issue (Pedlar et al. 2012).

Examples of adaptation tactics are:

- Creation of large group openings to increase regeneration of intolerant species
- Transitioning plantations to more complex systems by underplanting or promoting regeneration of a variety of native species expected to well under future climate
- Variable density thinning to create more diversity of age or size classes

Approach 7.3: Promote species with enhanced carbon density in woody biomass

Favoring tree species with higher wood densities, such as managing for hardwood species in forest types or natural communities where hardwood and conifer species co-occur, may increase carbon density and storage at stand levels (Bunker et al. 2005). Many areas of natural forest have been planted to even-aged conifer plantations, due to relatively fast growth and ability to produce timber, with resulting decreases in forest carbon stocks relative to natural forests (Liao et al. 2010) or naturally regenerated hardwood stands (Gahagan et al. 2015). Increasing the cover of hardwood species within conifer plantations, or the transition to natural forest stands following harvest may increase carbon stocks, as well as reduce potential carbon loss from greater risk of disturbance–induced mortality in even-aged conifer stands relative to natural hardwood stands (Domec et al. 2015).

Examples of adaptation tactics are:

- Creating large gaps in conifer dominated stands to encourage regeneration of oak species
- Planting hardwoods following harvest within conifer plantations

Approach 7.4: Introduce species or genotypes that are expected to be adapted to future conditions

Transitioning to a better-adapted system in order to maintain carbon sequestration capacity may involve the active introduction of species or genotypes to areas that they have not historically occupied, often described as assisted migration, assisted colonization, or managed relocation (Schwartz et al. 2012). One type of assisted migration, sometimes called forestry-assisted migration, focuses on moving species to new locations in order to maintain forest productivity and health under climate change (Pedlar et al. 2012). Given the uncertainty about specific climate conditions in the future, relocating species with a broad range of tolerances (e.g., temperature, moisture) from across a wide geographic range may be more successful. Moving species to new habitats within their current range or over relatively short distances outside their current range, and focusing on widespread species for which much is known about their life history traits, may be considered relatively low risk (Pedlar et al. 2012). However, there are still risks associated with moving any species, such as introducing new pests or diseases, the potential for hybridization with other closely related species, and genetic bottlenecks if the introduced seed source is not adequately diverse (Aubin et al. 2011).

Examples of adaptation tactics are:

- Planting oaks, pines, and other drought-tolerant species on sites that are expected to become drier and that have not been historically occupied by those species
- Planting flood-tolerant species on sites that are expected to become more prone to flooding and that are currently not occupied by flood-tolerant species
- Planting southern species, such as shortleaf pine, north of its current range on suitable sites based upon its projected range expansion
- Planting disease-resistant cultivars of American elm or American chestnut where they are likely to have suitable habitat.

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