

## Practitioners Menu of Adaptation Strategies and Approaches for Carbon Management

*Authors: **Todd A. Ontl** (tontl@fs.fed.us), **Chris Swanston** (cswanston@fs.fed.us), **Maria Janowiak** (mjanowiak02@fs.fed.us), **Jad Daley** (jdaley@americanforests.org)*

Forests play a critical role in sequestering carbon from the atmosphere, helping mitigate rising atmospheric carbon dioxide (CO<sub>2</sub>) 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 et 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 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, 2<sup>nd</sup> edition*; and the corresponding online interactive tool: [adaptationworkbook.org](http://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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## Using the Menu of Adaptation Strategies and Approaches

### 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
- 1.2 Reforest lands that have been deforested and afforest suitable lands
- 1.3 Increase the extent of forest cover within urban areas

### **Strategy 2: Reduce carbon losses through decreased natural disturbance, including wildfire**

- 2.1 Restore or maintain fire in fire-adapted ecosystems
- 2.2 Establish natural or artificial fuelbreaks to slow the spread of catastrophic fire
- 2.3 Alter forest structure or composition to reduce the risk, severity or extent of wildfire
- 2.4 Reduce the risk of tree mortality from biological or climatic stressors in fire-prone systems
- 2.5 Maintain or improve the ability of forests to resist pests and pathogens
- 2.6 Alter forest structure to reduce severity or extent of wind and ice damage

### **Strategy 3: Enhance forest recovery following disturbance**

- 3.1 Promptly revegetate sites after disturbance
- 3.2 Maintain or restore diversity of native species
- 3.3 Reduce competition for moisture, nutrients, and light
- 3.4 Protect future-adapted seedlings and saplings
- 3.5 Guide changes in species composition at early stages of development to meet expected future conditions

### **Strategy 4: Prioritize management of locations that provide high carbon value across the landscape**

- 4.1 Manage sites with low vulnerability to carbon loss for maintaining high carbon density
- 4.2 Create managed reserves on sites with high carbon density
- 4.3 Increase redundancy of important sites for existing carbon stocks across the landscape

### **Strategy 5: Maintain or enhance existing carbon stocks while retaining forest character**

- 5.1 Reduce impacts to soils and nutrient cycling
- 5.2 Maintain or restore hydrology
- 5.3 Prevent the introduction and establishment of invasive plant species and remove existing invasives
- 5.4 Increase stocking of understocked lands
- 5.5 Adjust harvest frequency and intensity according to risk of tree mortality
- 5.6 Increase structural complexity through retention of carbon stocks in living and dead wood
- 5.7 Disfavor species that are distinctly maladapted
- 5.8 Manage for species and genotypes with wide moisture and temperature tolerances
- 5.9 Promote species and structural diversity to enhance carbon capture and storage efficiency

### **Strategy 6: Enhance or maintain sequestration capacity through significant forest alterations**

- 6.1 Use seeds, germplasm, and other genetic material from across a greater geographic range
- 6.2 Alter forest composition and/or structure to maximize carbon stocks

6.3 Favor existing species or genotypes that are better adapted to future conditions

6.4 Promote species with enhanced carbon density in woody biomass

6.5 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 stocks, 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-establish 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).

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.

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

Reforestation is the intentional replanting of understocked forestlands. 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·yr<sup>-1</sup> (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·yr<sup>-1</sup> 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·yr<sup>-1</sup> (13-21 million metric tons C) within forest topsoils. 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·ha<sup>-1</sup>·yr<sup>-1</sup> (Post and Kwan 2000).

Examples of adaptation tactics are:

- Replanting following disturbances that have impacted natural regeneration and resulted in understocked stands.
- Establishing plantations on marginal croplands.
- The establishment of riparian buffers adjacent to agricultural lands

### *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; Jo and McPherson 1995). Carbon sequestration rates in urban areas can exceed those in natural forests due to greater foliar biomass, reduced competition from lower tree densities and irrigation and fertilization—and a changing climate may be further accelerating these growth rates in urban areas (Pretzsch et al. 2017). Trees can have an additional important influence on carbon mitigation in urban zones by reducing the energy 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:

- Planting urban trees properties adapted to future conditions in parks, adjacent to roadways, or in residential

### *Strategy 2: 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 natural disturbance 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). 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). 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). This strategy aims to avoid or reduce forest carbon losses through management actions intended to decrease natural disturbance frequency, extent, intensity, or severity.

#### *Approach 2.1: 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 less carbon emitted compared to wildfire (Agee et al. 2005). Additionally, prescribed fires limit the intensity or extent of wildfire if one were to occur. 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 projected seasonal precipitation changes to reduce risk of unintended fire conditions

#### *Approach 2.2: 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 2.3: 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 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
- Reducing tree density to lower fuel loading and maintain open conditions in ecosystems at lower elevations to reduce risk of fire at higher elevations
- Thinning to increase height to live crown to create forest structure that is expected to be less vulnerable to severe wildfire

#### *Approach 2.4: 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, or other climate-related disturbances greatly increases fuel loads and the risk of wildfire. 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 or density of a host species for a pathogen or insect pest

#### *Approach 2.5: 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<sup>-1</sup> 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 pest's 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 2.6: 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

### Strategy 3: 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 long-term 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 resilience of ecosystems, augmenting the ability of plant communities to initiate carbon recovery quickly following disturbance.

#### Approach 3.1: 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 short-term carbon loss from soil erosion. Prompt revegetation of sites following disturbance can reduce losses from 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:

- Planting 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 3.2: Maintain or restore diversity of native species*

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.
- 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 3.3: 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<sub>2</sub>) 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:

- Preventing or removing undesired species including invasive nonnative or aggressive native species

#### *Approach 3.4: 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 (Duvénck & Scheller 2015; Hof et al. 2017).

Examples of adaptation tactics are:

- Using repellent 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 3.5: 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

#### Strategy 4: 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, and how these elements influence plant community composition and carbon flux processes. 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, sites that can sustain high densities of aboveground biomass, or translocation of carbon from adjacent sites, such as soil deposition in floodplains. Additionally, sites may have high carbon densities from reduced carbon losses, such as site hydrology that results in saturated soil conditions that limit decomposition and result in 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 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 4.1: Manage sites with low vulnerability to carbon loss for maintaining high carbon density

Natural disturbance induced tree mortality from drought, pests and pathogens, fire, windthrow, or other disturbances are important for 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 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, 2) site hydrology or soil fertility that reduces drought or nutrient limitation impacts to forest productivity, or 3) enhanced species or structural diversity that may lower vulnerability or enhance recovery from impacts from pests or pathogens.

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

#### *Approach 4.2: 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

#### *Approach 4.3: Increase redundancy of important site for existing carbon stocks across the landscape*

The unpredictability of natural disturbance events across forested landscapes, along with unforeseen interactions between management, climate change, and forest dynamics mean some losses of carbon on sites with high carbon value is inevitable. Increasing redundancy of systems with high carbon values, either due to lower vulnerability to disturbance-induced losses or from high carbon densities, can lower overall risk of or carbon losses at broad scales.

Examples of adaptation tactics are:

- Restoring or increasing the occurrence of sites with community types with high carbon value
- Expanding the boundaries of reserves to core size
- Designation of buffer zones of low-intensity management around core reserve areas

#### Strategy 5: Maintain or enhance existing carbon stocks while retaining existing forest character

Many best management practices in forestry 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 strategy seeks to sustain or enhance ecological functions while retaining the current forest conditions to reduce the impacts of a changing climate on forest carbon stocks.

##### Approach 5.1: 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, physical and chemical changes to soils can result from disturbance, 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 impact 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 5.2: Maintain or restore hydrology*

Interdependency between carbon and water cycles within forest ecosystems is well recognized; adequate soil moisture is necessary for maintaining growth and productivity of forests, while trees help regulate rainfall by recharging atmospheric moisture through 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 rates, 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 may be susceptible to 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. In particular, infrastructure will need to be designed to accommodate greater hydrologic extremes in the future. 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

#### *Approach 5.3: 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 is 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 5.4: Increase stocking of understocked lands*

Increasing stocking levels on 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

#### *Approach 5.5: Adjust harvesting frequency or intensity according to risk of tree mortality*

When risk of carbon loss from natural disturbance is low, maintaining greater carbon stocks can provide significant carbon benefits over long periods of time (Galik and Jackson 2009). Greater carbon stocks can be achieved through increased rotation length (Duveneck and Scheller 2016;

Mika and Keeton 2015; Law and Waring 2015) or duration of time between harvest entry (D'Amato et al 2011), in addition to high 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). However, if a stand has high vulnerability to disturbance such as drought, fire, or insect mortality, shortening rotation lengths may provide the greatest carbon benefits by maintaining moderate levels of ecosystem carbon stocks over long time periods while minimizing the risk of large carbon losses if disturbance does occur (Wang et al 2013). 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. 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 stand densities (e.g., thinning) may reduce vulnerability to carbon losses from disturbance 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).

Examples of adaptation tactics are:

- Thinning even-aged stands to reduce competition for limiting soil moisture on drought-prone sites
- 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
- Decreasing rotation length of jack pine stands from 70-80 years to 50 years in fire-prone systems

#### *Approach 5.6: Increase structural complexity through retention of carbon stocks 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). 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 (Ford and Keeton 2017; Mika and Keeton 2015; Palik et al. 2014). Additionally, down 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

#### *Approach 5.7: 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 annual carbon sequestration can result from resource-use efficiencies from increased diversity of tree species (Ammer 2018; Curtis and Gough 2018), 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 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).

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
- 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

#### *Approach 5.8: 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. 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, although healthy individuals can be retained as legacies 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 5.9: Manage for species and genotypes with wide moisture and temperature tolerances*

Inherent scientific uncertainty surrounds climate projections at finer spatial scales (Schiermeier 2010), making it necessary to base decisions upon a wide range of predictions of future climate. 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:

- 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 confers with wide ecological tolerances

### Strategy 6: Enhance or maintain sequestration capacity through significant forest alterations

Land managers already work in many ways to increase forest productivity through enhancing structural and species diversity. As an adaptation strategy for managing forest carbon this general goal receives added effort and focus when managing systems whose characteristics limit the ability of the forest to sequester carbon or increase risks of carbon losses through disturbance. 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. 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 6.1: 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). 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. Although this strategy may require 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
- Identifying and communicating needs for new or different genetic material to seed suppliers or nurseries
- Planting seedlings germinated from seeds collected from various locations throughout a species' native range.

#### *Approach 6.2: Alter forest composition and/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 (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 (Duvénck and Scheller 2016; O'Hara and Ramage 2013). Altering forest stand characteristics, including 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).

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 6.3: Favor existing species or genotypes that are better adapted to future conditions*

For a particular site of forest type, there are likely many native species that may be well adapted to the future range of climatic conditions (Landscape Change Research Group 2014, Walk et al. 2011). Large reductions in carbon can occur with some natural disturbances and can result in species composition changes. Favoring or restoring native 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). Establishing or emphasizing future-adapted species now

may create opportunities to fill the niche left by 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 6.4: 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 (Liao et al. 2010). Increasing the cover of hardwood species with conifer plantations, or 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

#### *Approach 6.5: 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, the likelihood of success may be increased by relocating species with a broad range of tolerances (e.g., temperature, moisture) from across a wide range of provenances. Because this approach moves species to new habitats within their current range or over relatively short distances outside their current range, and focuses on widespread species for which much is known about their life history traits (Pedlar et al. 2012), it is generally considered relatively low risk. 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 within the current range that are expected to become drier and that have not been historically occupied by those species
- Planting flood-tolerant species, such as swamp white oak and silver maple, 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 elm or chestnut where they are likely to have suitable habitat.

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