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Review article

Adaptation strategies and approaches for forested watersheds

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ABSTRACT

Intentional climate adaptation planning for ecosystems has become a necessary part of the job for natural resource managers and natural resource professionals in this era of non-stationarity. One of the major challenges in adapting ecosystems to climate change is in the translation of broad adaptation concepts to specific, tangible actions. Addressing management goals and values while considering the long-term risks associated with local climate change can make forested watershed management plans more robust to uncertainty and changing conditions. We provide a menu of tiered adaptation strategies, which we developed with a focus on forests of the Midwest and Northeastern U.S., as part of a flexible framework to support the integration of climate change considerations into forested watershed management and conservation activities. This menu encapsulates ideas from the literature into statements that signify climate adaptation intention and provide examples of associated tactics to help ground the concepts in specific actions. Finally, we describe two demonstration projects, shared through the Northern Institute of Applied Climate Science's Climate Change Response Framework, that have used this Forested Watershed Adaptation Menu and Adaptation Workbook in project-level planning.

1. Introduction

Forested watersheds are expected to respond to the changing climate with shifts in species assemblages (Prasad et al., 2014; Swanston et al., 2018) and watershed hydrologic processes in ways that may challenge traditional expectations of water yield and water quality (Vose et al., 2016; Creed et al., 2014; Poff and Zimmerman, 2010). The direct effects of warming temperatures and variable precipitation are also likely to present challenges in upholding traditional resource values such as protecting cultural resources, enhancing biodiversity, sustaining productive timber, and provisioning habitat for wildlife and rare species. These challenges are likely to vary across scale, such that regional trends and climate projections may be greatly modified at the site level by local biophysical characteristics, current and former land-use, and past management (Milly et al., 2015). Individuals and organizations tasked with managing these ecosystems may benefit from reexamining their priorities and objectives within the context of climate change and watershed responses at the particular scale of on-the-ground management.

Natural resource managers are often charged with meeting targets for near-term ecosystem services even as they work to restore function lost to disturbance or past management, and pursue multi-decadal goals and desired future conditions. Climate change becomes an added challenge that amplifies existing stressors, potentially increasing the rate and magnitude of ongoing change. These interactions and feedbacks are of particular concern in vulnerable and degraded sites with low adaptive capacity (Mengistu et al., 2013). For example, shrinking snowpack and earlier spring melting in a primarily snow-fed watershed may reduce baseflow and the supply of available water throughout increasingly warm growing seasons. These changes can interact with existing infrastructure-related habitat fragmentation issues to further reduce hydrologic connectivity for aquatic wildlife and compound degradation of aquatic habitat. Given this challenge, proactive preparation to anticipate and accommodate change in long-term management planning can help natural resource managers maintain watershed values while creating options for future managers. Some natural resource

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managers may decide not to alter their management practices in the near-term after weighing projected long-term climate impacts and stressors on the function of forested watersheds. Others may choose to actively accommodate change while attempting to ensure continued ecosystem function and provision of services. The overarching goal of this work is to help individuals and organizations within a diverse management community clearly articulate their decisions and how they have intentionally considered climate change, risk, and adaptation in their management.

2. Menu of adaptation strategies and approaches

Two major challenges in the practice of climate adaptation are (1) translating broad adaptation concepts (Millar et al., 2007) to specific, tangible actions (Swanston et al., 2016), and (2) clearly and explicitly identifying the adaptation intent of an on-the-ground action. We developed an adaptive management process and step-by-step Adaptation Workbook in 2012 (Swanston and Janowiak, 2012; Swanston et al., 2016) that helps practitioners identify adaptation actions that address perceived climate threats and opportunities in pursuance of their stated management objectives. We also developed a series of adaptation menus that help people link their actions to broader adaptation strategies that align with their values and objectives, generally define success, and explicitly identify intent (Swanston et al., 2016). Each menu addresses a different resource area, using relevant and appropriate terms, strategies, approaches, and example tactics. Although the menu concepts focus on adaptation to climate change, the ideas are rooted in fundamental principles of natural resources management (Creed et al., 2011) and may also provide co-benefits to various conservation efforts and greenhouse gas mitigation goals. Critically, the menus are not guidelines and do not make recommendations. They instead represent numerous approaches to resource management that are often complementary, but always chosen by the user as they deem appropriate.

This menu approach emphasizes flexibility and user judgment, rather than specific guidelines or recommendations, to accommodate diverse values, management goals, geographic settings, local site conditions, and other management considerations. Natural resource managers can use these menus to choose the approaches that are most suitable to a particular management goal and ecosystem type. Importantly, the Adaptation Workbook and menus do not compel or influence natural resource managers to change their ecosystems or adopt new practices; instead they help mangers make intentional, climate-informed decisions best suited to their objectives, constraints, and perception of climate risks and opportunities. Our objectives in the current project were to (1) create a Forested Watershed Adaptation Menu that supports natural resource managers working on projects in forested areas related to riparian and aquatic habitat management, hydrologic function, infrastructure improvements, and recreation; and (2) demonstrate the viability of the Forested Watershed Adaptation Menu for use with real-world management projects by developing adaptation demonstration projects (Janowiak et al., 2014).

3. Methods – developing the menu – design and outreach

We designed a three-step process to synthesize current perspectives on adaptation and develop climate adaptation strategies and approaches relevant to rural forested watershed management in the Midwest and Northeastern U.S. forests: (1) we conducted listening sessions with natural resources professionals; (2) we reviewed literature to identify and define adaptation strategies and approaches, drawing upon themes that emerged in step 1 to refine searches; (3) we vetted the adaptation strategies in multiple outreach engagements with scientists and natural resource managers. We applied this process iteratively June 2016 through February 2018. Informal individual listening sessions were conducted with 55 regional practitioners from the Midwest and Northeast (representing federal (27), state (5), tribal (8), NGO (7), and academic (8) perspectives). The purpose of the listening sessions was to gain understanding and examples of (1) perception of climate-related risks to local resources, (2) perception of anticipated climate-related challenges and opportunities relevant to management objectives, and (3) locally specific adaptation actions. We first identified major topics that emerged from the listening sessions (see Supplemental materials), and categorized them into broad themes related to forested watershed management such as: “hydrologic connectivity”, “streamflow”, “water yield”, “water quality”, “wetlands”, “lakes”, “invasive species and pests”, “forest and riparian area management”, “infrastructure (roads, stream-crossing)”, “low impact infrastructure and green infrastructure”. We developed initially broad search terms from the themes with the intent of capturing a larger volume of generally relevant articles: “water, hydrology, riparian forest management, climate change adaptation.” We entered these terms into Google Scholar search engine to identify initial literature (26,900 articles). We subsequently and iteratively filtered these results into increasingly specific and relevant lists. This search process resulted in a total of 539 peer-reviewed articles, book chapters, and reports that address the continuum of climate vulnerability to adaptation actions as related to forested watersheds.

We collated strategies and tactics from the listening sessions and literature search into a tiered list based on the approach of the Forest Adaptation Menu (Janowiak et al., 2014; Swanston et al., 2016; Ontl et al., 2018). Our definitions of strategy, approach, and tactic are consistent with the adaptation literature (Swanston and Janowiak, 2012; Swanston et al., 2016); such that strategies provide added specificity to broad adaptation options (Millar et al., 2007) and are defined as “adaptation responses that are appropriate to broad hydrologic and ecological conditions and overarching management goals”; approaches are defined as “more detailed adaptation responses with consideration of site conditions and management objectives”; and tactics are defined as “prescriptive actions designed for specific site conditions and management objectives”. This structure of tiered strategies and approaches is called the Menu of Adaptation Strategies and Approaches for Forested Watersheds (“menu”), described in following sections (Table 1). In step 3 of this process we vetted the menu in two working group sessions at regional and national climate adaptation conferences during 2017 to solicit feedback (65 participants). We then vetted the menu using real-world natural resource management projects at three in-person, 2-day adaptation planning workshops. The 122 participants in the workshops used the menu and the Adaptation Workbook (Swanston et al., 2016) to customize adaptation tactics for their forest management projects on a combined > 141,000 ha. The menu was iteratively refined using feedback from each outreach engagement. Supplementary Materials provide for more details on the process, including example listening session questions and workshop agendas. Two projects from the workshops were chosen as adaptation demonstrations and described below to illustrate the application of the menu in a real-world setting.

4. Adaptation menu for forested watersheds

4.1. Using the adaptation strategies and approaches

4.1.1. The adaptation strategies and approaches can provide

1) A spectrum of possible adaptation actions that can help sustain healthy, forested watersheds and achieve management goals in the face of climate change, 2) A menu of adaptation actions from which natural resource managers select actions best suited to their specific management goals and objectives, 3) A platform for discussing climate change-related topics and adaptation methods, 4) Example tactics that could potentially be used to implement an approach, recognizing that specific tactics will be designed by the natural resource manager.

4.1.2. The adaptation strategies and approaches do not

1) Make recommendations or set guidelines for management

Table 1
Menu of forested watershed strategies and approaches. A “Strategy” is a broad adaptation response that is applicable across a variety of resources and sites, and an “Approach” is more specific to a resource issue or geography. Professional natural resource managers use the menu in association with the Adaptation Workbook (Swanston et al., 2016) to define “tactics” (not represented in the table). Tactics are developed by the land manager and are considered the most specific adaptation response. A tactic describes on-the-ground actions that can be implemented.

List of forested watershed adaptation strategies and approaches.
Strategy 1: Sustain fundamental hydrologic processes
Approach 1.1: Maintain and enhance infiltration and water storage capacity of forest soils
Approach 1.2: Maintain and restore hydrologic connectivity
Approach 1.3: Maintain and restore stream channel form and function
Approach 1.4: Maintain and restore floodplain connectivity
Approach 1.5: Maintain and restore forested wetlands and lowland areas
Strategy 2: Maintain and enhance water quality
Approach 2.1: Moderate surface water temperature increases
Approach 2.2: Reduce export and loading of nutrients and other pollutants
Approach 2.3: Reduce soil erosion and sediment deposition
Strategy 3: Maintain or restore forests and vegetative cover
Approach 3.1: Maintain or restore forest and vegetative cover in riparian areas
Approach 3.2: Promptly revegetate areas after disturbance
Approach 3.3: Maintain or improve the ability of forests to resist pests and pathogens
Approach 3.4: Prevent invasive species establishment and remove existing invasive species
Approach 3.5: Prioritize and maintain unique habitats for refugia
Approach 3.6: Enhance species age classes and structural diversity in forests
Approach 3.7: Identify, maintain, and enhance important habitats for fish and wildlife
Strategy 4: Facilitate forest ecosystem adjustments through species transitions
Approach 4.1: Favor or restore native species that are expected to be adapted to future conditions
Approach 4.2: Establish or encourage new mixes of native species
Approach 4.3: Disfavor species that are distinctly maladapted
Approach 4.4: Introduce species that are expected to be adapted to future conditions
Approach 4.5: Move at-risk species to locations that are expected to provide habitat
Strategy 5: Accommodate altered hydrologic processes
Approach 5.1: Manage systems to cope with decreased water levels and limited water availability
Approach 5.2: Enhance the ability of systems to retain water
Approach 5.3: Adjust systems to cope with increased water abundance, and high water levels
Approach 5.4: Respond to or prepare for excessive overland flows (surface runoff)
Strategy 6: Design and modify infrastructure to accommodate future conditions
Approach 6.1: Reinforce infrastructure to meet expected conditions
Approach 6.2: Reroute or relocate infrastructure, or use temporary structures
Approach 6.3: Incorporate natural or low impact development into designs
Approach 6.4: Remove infrastructure and readjust system

decisions. It is up to the natural resource manager to decide how this information is used, 2) Express preference for any strategies or approaches within an ecosystem type, location, or situation. Rather, a combination of location-specific factors and manager expertise is needed to inform the selection of any strategy or approach.

4.2. Strategy 1: Sustain fundamental hydrologic processes

This strategy seeks to sustain fundamental watershed functions, addressing the maintenance of and restoration of soil-water connections and hydrologic function. A shift in climate may amplify and exacerbate existing ecosystem challenges resulting from land-uses that have fragmented, altered or obstructed water flow pathways. Sustaining hydrologic and ecosystem functions into the future is likely to depend on management planning that seeks to maintain the long-term conveyance of water through unobstructed hydrologic pathways, most notably actions that promote the enhancement of water infiltration by porous forest soils (Creed et al., 2011; Furniss et al., 2010).

4.2.1. Approach 1.1: Maintain and enhance infiltration and water storage capacity of forest soils

Undisturbed forest floors with porous soils capture, absorb, and slowly release water to groundwater, and downstream sources, providing critical regulation of water quality, and quantity, including the attenuation of flood flows (Neary et al., 2009; Smith et al., 2016). Climate change is projected to cause more frequent and intense rain events in the Midwest and Northeastern U.S., increasing rates of erosion, runoff and soil losses (Nearing et al., 2004; Wuebbles et al., 2017; Yin et al., 2018). This further increases the need to minimize soil exposure and to protect soil properties that enhance infiltration. Many existing guidelines and best management practices (USFS, 2012) describe actions that can be used to enhance soil-water infiltration; and many of these actions are also likely to be beneficial in the context of climate adaptation, either in their current form or with modifications to address potential climate change impacts. *Examples of adaptation tactics are*: 1) Leave dead and downed wood (coarse woody debris) in the uplands and riparian areas to enhance moisture, and soil; 2) Modify forest operations techniques and equipment with pallets, debris mats, or float bridges, to minimize soil compaction, rutting, or other impacts to sensitive ecosystems, surface water bodies, soils and residual trees.

4.2.2. Approach 1.2: Maintain and restore hydrologic connectivity

Water moves through surface and subsurface flow pathways, some permanent and others more dynamic (Creed et al., 2011). Shifts in precipitation timing and intensity are expected to alter water flow pathways and result in more frequent low or zero flow days in drier seasons (Demaria et al., 2016). This could transform perennial networks to intermittent, and especially affect ephemeral and intermittent systems known to have less water storage potential (e.g. *headwater catchments*) (Mengistu et al., 2013; Jaeger et al., 2014). As the climate continues to change, addressing hydrologic connectivity in forest management may help to sustain water quality and storage, enhance the transfer of sediment and nutrients, and offer thermal protection and migration pathways for organisms (Creed et al., 2011; Mengistu et al., 2013; Capon et al., 2013; Jaeger et al., 2014; Ficke et al., 2007; Perry et al., 2015). *Examples of adaptation tactics are*: 1) Mechanically treat compacted soils to help restore natural patterns of hydrologic flow (Andrus and Froehlich, 1983); 2) Replace undersized stream-crossings that constrict streamflow and inhibits aquatic organism passage between upstream and downstream water sources to enhance organism movement into more favorable habitats (e.g. seasonal habitats, off-channel or cool-water areas) (Furniss et al., 2010).

4.2.3. Approach 1.3: Maintain and restore stream channel form and function

Streams and rivers are dynamic and sensitive to climate and land-cover, where changes are often reflected in physical alterations to the stream channel geomorphology (*channel shape and pattern*) and to fluvial processes (*streamflow and sediment transport*). More intense and variable seasonal precipitation is expected to increase volume and rate of water entering streams, amplifying the risks of erosion, scour, and adjustment of channel dimensions, particularly bankfull width, and depth (Montgomery and Buffington, 1998; Wilhere et al., 2017). Warmer conditions and altered forest hydrology may combine to reduce low flows during the growing season, potentially fragmenting aquatic and terrestrial wildlife communities (Demaria et al., 2016; Demaria et al., 2016). Restoring stream channel form and function and preparing riparian systems to absorb additional climate-related stresses, may help reduce risks of erosion, channel instability, and degradation of aquatic habitat (Williams et al., 2015; Palmer et al., 2009). *Examples of adaptation tactics are*: 1) Remove anthropogenic “hard measures” that restrict channel flow and alter channel shape such as check dams, concrete armoring and undersized culverts; and replace with structures designed to accommodate a natural stream channel that allows for geomorphic adjustment over time (Rosgen, 2007); 2) Use in-stream restoration techniques to dissipate streamflow energy that enhances bank stability during and after large storm events, by using rock vanes, weirs, large boulders and large wood (Yochum, 2017).

4.2.4. Approach 1.4: Maintain and restore floodplain connectivity

Floodplains, wetlands, lowland forests, and riparian vegetation are critical water storage areas that also enhance local water quality by filtering pollutants, and sediments. Floodplain systems reduce the magnitude of flood events by physically slowing water velocity as it overtops channel banks, a process that regulates downstream water quantity and streamflow velocity (Dunne and Leopold, 1978). Additionally, this regulation may improve base flow conditions that can buffer forested ecosystems during droughts (Isaak et al., 2015). Higher peak flows and longer dry periods are both occurring as the climate changes (Melillo et al., 2014; Huang et al., 2017), potentially increasing the importance of maintaining and restoring floodplain connectivity to stream networks. *Examples of adaptation tactics are*: 1) Reconnect floodplains adjacent to incised river channels using stream restoration techniques to restore bankfull conditions (Yochum, 2017; Rosgen, 2007); 2) Restore woody corridors in floodwater storage areas between riverbanks and levees to reduce floodwater damages (Allen et al., 2003).

4.2.5. Approach 1.5: Maintain and restore forested wetlands and lowland areas

Forested wetland and lowland forest communities can be regionally unique, highly diverse, and adapted to local hydrologic regimes; and therefore sensitive to climate changes that may modify wetland hydroperiod (patterns of water depth, duration, frequency, seasonality (Erwin, 2008; Tillman and Siemann, 2011; Vanderhoof et al., 2018). Altered hydrology may challenge native species reproduction and present opportunities for undesirable species competition, invasive species establishment and pests invasion (Erwin, 2008; Junk et al., 2012; Galatowitsch et al., 2009). Restoring and prioritizing protection of wetlands and lowland areas may increase the adaptive capacity of watersheds to moderate flood peak flows, provide storage of floodwaters, and regulate water supply during drought (Furniss et al., 2010). *Examples of adaptation tactics are*: 1) Increase wetland species and structural diversity to reduce vulnerability and losses related to pest pressures; 2) Restore hydrology of previously drained wetlands by incorporating practices that increase absorption and retention of water; 3) Intensify invasive species removal (Galatowitsch et al., 2009).

4.3. Strategy 2: Maintain and enhance water quality

This strategy addresses the additional efforts necessary to sustain clean water in a changing climate, with an emphasis on anticipating and preventing increased stresses before water quality impairment occurs. Natural resource managers may already implement actions that avoid degradation to water quality, but water quality is expected to change, possibly worsen in some areas due to changes in seasonal precipitation regimes and warming (Sinha et al., 2017). As hydrology and ecosystems change reflecting a changing climate, these changes are likely to combine with existing land-use issues to further degrade or diminish water quality (Whitehead et al., 2009). These changes may result in altered water chemistry, increased mobilization of pollutants and sediments to surface waters, altered pollutant resident times, and increasing water temperatures (Murdoch et al., 2000; Whitehead et al., 2009; Georgakakos et al., 2014; Knouft and Ficklin, 2017).

4.3.1. Approach 2.1: Moderate surface water temperature increases

Climate change is projected to increase surface water temperatures and alter hydrologic regimes, increasing the risks of degraded water chemistry and anoxic conditions, which can in turn result in reduced habitat quality and aquatic organism mortality (Ficke et al., 2007). Some aquatic species are expected to expand into new areas as they seek refuge, while others may be at risk if they are unable to migrate or withstand and adapt to changing thermal conditions at a sufficient rate (Ficke et al., 2007; Comte and Olden, 2017). Efforts to offset warming temperatures in riparian corridors and within sensitive systems, may reduce the extent of water warming and offset some evaporative losses (Story et al., 2003; Furniss et al., 2010; Reiter et al., 2015; Williams et al., 2015). *Examples of adaptation tactics are*: 1) Establish or widen existing riparian areas to increase canopy coverage shading surface waters, particularly on headwater and low order streams (Reiter et al., 2015); 2) Adjust outlet height on dams to release cold water from lakes or reservoirs.

4.3.2. Approach 2.2: Reduce export and loading of nutrients and other pollutants

A changing climate coupled with land-use change is expected to influence the export and loading of nutrients and pollutants in surface waters. In particular, increasing temperatures and more variable precipitation may intensify pollutant concentrations in soils and surface waters, accelerating eutrophication (Ficke et al., 2007; Havens et al., 2016; Sinha et al., 2017), increasing risks to conserving soil quality, (National Research Council, 2008; Norton et al., 2010), and altering the transport and residence time of pollutants (Ficke et al., 2007; Nelson et al., 2009; Palmer et al., 2009; Sinha et al., 2017). Freshwater systems are heavily influenced by nutrient exports from agricultural and urban land-uses and to a lesser extent from forest management and forest disturbances (Swank and Vose, 1997; NRC, 2008; Bechtold et al., 2016). Actions that enhance the ability of the ecosystem to retain nutrients or otherwise intercept the export of pollutants to surface waters may become increasingly important to sustain a quality of water at or below critical thresholds. *Examples of adaptation tactics are*: 1) Afforest shorelines of open surface waters (such as lakes, open wetlands), to reduce nutrient runoff and wind action (wind can shear sediments and turnover inorganic solids known to stimulate cyanobacteria blooms) (Havens et al., 2016); 2) Avoid or reduce the risk of organic supplements (e.g. manure), nutrient or chemical delivery to surface water or groundwater when treating areas near waterbodies. (NRC, 2008; USFS, 2012).

4.3.3. Approach 2.3: Reduce soil erosion and sediment deposition

Erosion is anticipated to increase as seasonal precipitation and storm intensities change, altering soil moisture regimes, and runoff (Nearing et al., 2004; Yin et al., 2018). Sites already prone to erosion may have increased risks of sediment losses in a changing climate, particularly sites with sparse canopy, sparse litter cover, steep slopes, and impervious surfaces (Palmer et al., 2009; Routschek and Schmidt, 2014). Excessive sedimentation and deposition of fine materials can negatively influence watershed hydrology and flow pathways, water quality (e.g. clarity, chemical composition), and potential survival and regeneration of plants, aquatic and terrestrial wildlife (Dunne and Leopold, 1978; Jones et al., 2012; Chapman et al., 2014; Kjelland et al., 2015). Best management practices to avoid soil losses can help prepare and protect sites from the added challenges associated with extreme events, increased frequency of rain events, seasonal variations in soil moisture and more frequent overland flows in all seasons (Furniss et al., 2010; Jiménez Cisneros et al., 2014). *Examples of adaptation tactics are*: 1) Maintain vegetation, or revegetate shoreline banks to absorb and dissipate water velocity and energy; 2) Slow road surface drainage and reduce sedimentation by directing water into forested or densely vegetated areas with lead off ditches, broad based dips, bioswales and water bars (Keller and Ketcheson, 2015; Strauch et al., 2015).

4.4. Strategy 3: Maintain or restore forests and vegetative cover

This strategy addresses the benefits of healthy forest cover in the production of water resources. It is well established that forested watersheds provide multiple benefits and ecosystem services such as timber, carbon storage, wildlife habitat, food, and cultural services. Changes to forest structure and composition, can alter underlying hydrologic processes within a watershed affecting the capture, storage and filtration of water, and the regulation of streamflow (NRC, 2008; Osterkamp and Hupp, 2010; Perry et al., 2015). Managing forests to reduce stressors, increase structural and species diversity, and protect unique habitats, may enhance forest ecosystem resilience to increasing climate variability, extreme events, and other disturbances.

4.4.1. Approach 3.1: Maintain or restore forest and vegetative cover in riparian areas

Forests located within riparian areas serve important ecosystem functions, such as reducing soil erosion, buffering high flows (Osterkamp and Hupp, 2010; Capon et al., 2013), regulating base flows (Reiman and Isaak, 2010) moderating stream temperatures, reducing evaporation from surface waters, and providing migration corridors for wildlife and plant species (Heller and Zavaleta, 2009; Capon et al., 2013; Mawdsley et al., 2009). Many of these functions and benefits are influenced by the riparian forest structure and species assemblage, and may be degraded if riparian forests undergo decline or exacerbated stress from climatic shifts and extreme events (Swanston et al., 2018). Changing conditions are already threatening regeneration processes for some species, and may result in failure of natural regeneration of desired species. Actions to maintain or restore vegetative cover will typically be consistent with existing best management practices and prescriptions for riparian management zones, but may require more active intervention to compensate for forest decline to promote healthy cover and function. *Examples of adaptation tactics are*: 1) Restore or promote a diversity of tree and plant species to increase stream shading, provide sources of woody debris, stabilize the soil, restore fluvial processes, and provide habitat and connectivity for wildlife; 2) Restore or reforest riparian areas adjacent to agriculture, or developed areas to reduce erosion, and nutrient loading to surface waters.

4.4.2. Approach 3.2: Promptly revegetate areas after disturbance

Potential increases in the frequency, intensity, and extent of large and severe disturbances may result in loss of forest cover, productivity, or function (Dale et al., 2001). Vigorous natural regeneration may be compromised, slowing recovery and potentially yielding competitive advantage to invasive or undesirable species. Prompt revegetation of sites following disturbance helps reduce soil loss and erosion, maintain water quality, and discourage invasive species in the newly exposed areas. These efforts can also provide an opportunity to promote natural regeneration or foster species that may be better adapted to future conditions. *Examples of adaptation tactics are*: 1) Creating suitable physical conditions for natural regeneration after disturbance through site preparation (such as chaining after a burn to promote seed establishment); 2) Planting species expected to be better adapted to future conditions and resistant to insect pests or present pathogens, especially where natural regeneration is affected by disturbance and is widely failing.

4.4.3. Approach 3.3: Maintain or improve the ability of forests to resist pests and pathogens

Even modest changes in climate may cause substantial increases in the distribution and abundance of many insect pests and pathogens, potentially leading to reduced forest productivity or increased tree stress and mortality (Ayres and Lombardero, 2000; Dukes et al., 2009; Ramsfield et al., 2016). Impacts may be exacerbated where site conditions, climate, and other stressors, interact to increase the vulnerability of forests to these agents (Spittlehouse and Stewart, 2003). Actions to manipulate the density, structure, or species composition of a forest may reduce susceptibility to some pests and pathogens (Spies et al., 2010). *Examples of adaptation tactics are*: 1) Thinning to reduce the density of a pest's host species to discourage infestation, based on knowledge that certain tree species are especially susceptible to pests and pathogens at particular stocking levels; 2) Using pesticides or biological control methods to manage pest populations (such as gypsy moth, hemlock woolly adelgid, Asian longhorned beetle) in heavily infested areas.

4.4.4. Approach 3.4: Prevent invasive species establishment and remove existing invasive species

Hundreds of nonnative invasive plant species are currently present in the Midwest and Northeast (Chornesky et al., 2005; NRCS, 2018). Climate change is projected to increase habitat for many of these species, which may be poised to outcompete native species (Chornesky et al., 2005; Millar et al., 2007; Hellmann et al., 2008). Current methods for controlling nonnative invasive species emphasize early detection and rapid response to new infestations (Hellmann et al., 2008). Management of highly mobile nonnative invasive species may require increased coordination across property boundaries and over larger geographic areas, and is likely to require an increasing budget for eradication efforts. Limitations in available resources may require managers to prioritize which species to eradicate and which species to allow to occupy a site. *Examples of adaptation tactics are*: 1) Eradicate existing populations or seed sources (e.g. upstream) of invasive plants through physical or chemical treatments; 2) Maintain closed-canopy conditions to reduce the ability of light-loving invasive species to enter the understory; 3) Install artificial movement barriers in connected migration areas to prevent spread of invasive species.

4.4.5. Approach 3.5: Prioritize and maintain unique habitats for refugia

Some sites have a sheltered topographic position, or have retained species through past periods of climate change (Keppel et al., 2012). These potential refugia are formed through spatial, geophysical, and biological variation on the landscape and may be identified as unique sites that are anticipated to be more resistant to change. These sites may provide the best chance to retain habitat for native species under future climate change (Anderson et al., 2012; Morelli et al., 2016). Species at these sites are not necessarily sensitive or at-risk, although they may face increased stress under future climate on some landscape positions. Committing additional resources may be necessary to protect characteristic site conditions from degradation by invasive species, herbivory, fire, or other disturbances. *Examples of adaptation tactics are*: 1) Identify and manage cooler and wetter locations that are expected to be more resistant to changes in climate as refugia for maintaining native plant communities (e.g. Hemlock) in the future; 2) Reduce harvest or management-related disturbances in areas that may be buffered from climate change (such as in groundwater spring-fed areas, sheltered slopes, swales or valleys with continuous shading).

4.4.6. Approach 3.6: Enhance species age classes and structural diversity in forests

Species are vulnerable to stressors at different stages in their life cycle. Even-aged stands are often more vulnerable to insect pests and diseases, many of which are likely to increase in range and severity as a result of climate change. Uneven-aged systems may expose a smaller proportion of the population to a particular threat at any one time, which can increase the resistance or resilience of a stand to a wider range of disturbances (O'Hara and Ramage, 2013). Maintaining a mix of ages, sizes, or canopy positions will help buffer the overall stand to stressors specific to a single age class (Noss, 2001). Likewise, stands with higher species diversity may be less vulnerable to climate change impacts and disturbances because they distribute risk among multiple species, reducing the likelihood that the entire system will decline or lose productivity even if one or more species suffer adverse effects (Duveneck et al., 2014). Even small increases in species diversity in low-diversity stands or communities may strongly increase resilience without distinctly altering species composition (Anderson and Chmura, 2009; Cadotte et al., 2012; Wilkerson and Sartoris, 2013). *Examples of adaptation tactics are*: 1) Emulate natural disturbances through forest harvest techniques such as variable-density treatments or irregular return intervals in order to encourage the development of multiple age cohorts, 2) Planting species with a diverse timing of phenological events (e.g. flowering, fruiting, leaf out, leaf drop) to provide necessary resources over a longer time frame to forest-dependent wildlife species.

4.4.7. Approach 3.7: Identify, maintain, and enhance important habitats for fish and wildlife

Climate change and future land-use changes are projected to significantly reorganize the composition and structure of natural communities by altering the timing, form, quality, and quantity of water resources (Knouft and Ficklin, 2017; Herb et al., 2014). Climate changes will interact with other challenges to terrestrial and aquatic habitats, including habitat fragmentation, loss, and water provisioning (Kampichler et al., 2012; Hansen et al., 2017). At the same time, changes in seasonal patterns and hydrology are expected to influence the timing and location of feeding, breeding, and other behaviors of terrestrial and aquatic organisms (Höök et al., 2018; Middleton and Souter, 2016). This could lead to a shift in areas that are currently considered 'habitat' for certain species. Identifying and maintaining habitats that can reliably provide resources may help to buffer the impacts and support terrestrial and aquatic organism survival throughout a range of climate extremes and long-term warming (Ficke et al., 2007; Mawdsley et al., 2009; Palmer et al., 2009; Capon et al., 2013). Likewise, enhancing habitat connectivity can provide fish and wildlife with options if existing habitats decline. *Examples of adaptation tactics are*: 1) Use water control structures to maintain the hydrologic function and regulate water levels and open water conditions when necessary for migratory birds and wildlife breeding areas; 2) Heavily manage invasive species, especially during wet periods when soils are moist and when invasive species may actively re-root.

4.5. Strategy 4: Facilitate forest ecosystem adjustments through species transitions

This strategy seeks to maintain overall ecosystem function and health by gradually enabling and assisting adaptive transitions of tree species and forest communities in suitable locations. Species composition in many forest ecosystems is expected to change as tree species adapt to a new climate (Swanston et al., 2018). Many of the approaches in this strategy attempt to mimic natural processes, but may currently be considered unconventional management responses. In particular, some approaches incorporate assisted migration, which remains a challenging and contentious issue (McLachlan et al., 2007; Ricciardi and Simberloff, 2009). It is suggested that natural resource managers thoroughly investigate potential consequences to the native ecosystem before attempting to introduce new species (Ricciardi and Simberloff, 2009). This strategy is best implemented with caution, incorporating due consideration of the uncertainties inherent in climate change, the sparse record of previous examples, and continued uncertainties of forest response. Outcomes from early efforts to transition communities can be evaluated to provide both information on future opportunities and specific information related to methods and timing.

4.5.1. Approach 4.1: Favor or restore native species that are expected to be adapted to future conditions

There are many cases where native species may be well adapted to the future range of climatic and site conditions (Walk et al., 2011; Prasad et al., 2014). Using management to favor native species in a community or forest type favoring species with wide ecological amplitude and persistence under a wide variety of climate and site conditions may enhance the system to fare better under future climate change, and can facilitate a gradual shift in the forest composition. Establishing or emphasizing future adapted species now may create opportunities to fill niches 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*: 1) Favor or establish oak, pine, and other more drought- and heat-tolerant species on ridge tops, south-facing slopes with shallow soils, or other sites that are expected to become warmer and drier; 3) Favor or plant species in wetlands that are resistant to desiccation, such as perennial species that spread by runners, and those with deep tap roots.

4.5.2. Approach 4.2: Establish or encourage new mixes of native species

Repeated periods of warming and cooling over the last 15,000 years have resulted in large shifts in species composition (Davis, 1983; Jacobson Jr et al., 1987; Shuman et al., 2002) Novel combinations of climatic and site conditions are projected to continue to affect individual species in different ways. Although some species may not occur in a forest or community type as currently defined, they may have been together previously. Novel mixing of native species may lead to the dissolution of traditional community relationships and result in conversion to a newly defined or redefined forest or community type (Davis et al., 2005; Root et al., 2003). *Examples of adaptation tactics are*: 1) Planting or seeding a mixture of native species currently found in the areas that are not typically grown together but may be a suitable combination under future conditions; 2) Allowing a species native to the region (e.g. black locust) to establish where it was not historically present, if it is already encroaching and likely to do well there under future climate conditions.

4.5.3. Approach 4.3: 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 especially vulnerable to habitat loss, and some of these species are projected to decline rapidly as conditions change (Iverson, 2002; Iverson and Prasad, 1998). Monitoring or inventory data for some species may already show evidence of decline at a particular site, although their decline may not be attributed to a single cause, but to a combination of causes that may include varying degrees of interaction with climate change. Models that incorporate climate change and species' life history characteristics may identify other species that are likely to decline (Prasad et al., 2014; Wang et al., 2014). Species declines may require rapid and aggressive management responses to maintain forest cover and ecosystem function during periods of transition. In ecosystems where the dominant species are likely to decline substantially or disappear, this may mean strongly altering the species assemblage through active or passive means. *Examples of adaptation tactics are*: 1) Removing unhealthy individuals of a declining species in order to promote other species expected to fare better. This does not imply that all individuals should be removed, and healthy individuals of declining species can be retained as legacies; 2) Anticipating and managing rapid decline of species with negative prognoses in both the short and long term (e.g., hemlock, ash) by having adequate seed stock of a desired replacement species expected to do well under future climate conditions.

4.5.4. Approach 4.4: Introduce species that are expected to be adapted to future conditions

Maintaining ecosystem function or transitioning to a better-adapted system 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 (Hoegh-Guldberg et al., 2008; Hunter, 2007; McLachlan et al., 2007; Ricciardi and Simberloff, 2009). 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; Seddon, 2010). 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. This approach is generally considered less risky than species-rescue assisted migration (see Approach 4.5) because it 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). 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*: 1) 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; 2) 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.

4.5.5. Approach 4.5: Move at-risk species to locations that are expected to provide habitat

The climate is changing more rapidly than some species can migrate, and the movement of species may be restricted by land-use or other impediments between areas of suitable habitat (Davis and Shaw, 2001; Iverson et al., 2004). This can be particularly challenging for species that are already rare or threatened. A subset of assisted migration, sometimes called species-rescue assisted migration, focuses on avoiding extinction of species threatened by climate change (Pedlar et al., 2012). If current habitat occupied by those species is expected to become (or already is) unsuitable, assisted migration to potential new suitable habitat may be the best option to promote the survival of the species (Vitt et al., 2010). Because such species are often extremely rare, this type of assisted migration can also potentially cause declines in the donor populations through removal of seeds or individuals (Aubin et al., 2011). This approach is best implemented with great caution, incorporating due consideration of the uncertainties inherent in climate change, the sparse record of previous examples, and continued uncertainties of forest response (Ricciardi and Simberloff, 2009). *Examples of adaptation tactics are*: 1) Planting or seeding a rare or threatened plant species that is at risk for extinction to a newly suitable habitat outside its current range; 2) Managing for culturally important species in areas where temperature and hydrologic conditions may be most suitable in the future (e.g. birch).

4.6. Strategy 5: Accommodate altered hydrologic processes

This strategy aims to help ecosystems adjust in response to fundamental changes in hydrologic processes altered by a changing climate. The timing, form, and spatial distribution of precipitation is changing with the climate, with cascading effects on forest hydrologic cycles that affect water yield and water quality (Wuebbles et al., 2017; Ficklin et al., 2016). Forest species assemblage, structure, and habitat quality will shift with changes in the nature and timing of water availability. Anticipating potential impacts to water levels and quality in management planning may help natural resource managers reduce risks and take advantage of opportunities to sustain hydrologic function. Broadly considering climate related alterations to the hydrologic cycle along with site-level responses and potential land-use changes is likely to provide the most complete picture of risks and opportunities (Palmer et al., 2009; Furniss et al., 2010; Auerbach et al., 2012; Sun and Vose, 2016).

4.6.1. Approach 5.1: Manage systems to cope with decreased water levels and limited water availability

Variable precipitation and warming is projected to affect the growing season water balance and may resulting in chronic or permanent water limited dry conditions, particularly in the late-growing season (Wuebbles et al., 2017). Limited water is of particular concern for habitats and food webs sensitive to altered timing and quantity of available water, such as aquatic species dependent on ecological flows for survival (Ficke et al., 2007; Poff and Zimmerman, 2010; Capon et al., 2013; Reiman and Isaak, 2010; Knouft and Ficklin, 2017). Repeated drought pressures can influence species assemblages, and habitat function negatively affecting forests unlikely to adjust to drier conditions (Swanston et al., 2018). Management that anticipates drier conditions in long-term watershed planning can capitalize on a system's inherent elasticity to lessen habitat degradation and enhance systems to persist under a range of conditions (Seavy et al., 2009; Auerbach et al., 2012; Perry et al., 2015; Elkin et al., 2015; Vose et al., 2016; Creed et al., 2014). Management responses to help systems cope with limited water may require innovation like selecting drought tolerant species and genotypes from drier habitats, reducing stocking levels, and modifying infrastructure and facilities to maximize water capture and storage. However, some treatments can further diminish water supply or may negatively affecting other ecosystem services (e.g. water quality, nutrient cycling and wildlife habitat). Therefore management decisions require careful attention to site conditions and characteristics to critically evaluate trade-offs (NRC, 2008; Ford et al., 2011; Grant et al., 2013; Vose et al., 2016; Clark et al., 2016; Kolka and Smidt, 2004). *Examples of adaptation tactics are*: 1) Reducing leaf area by thinning, and favoring a diversity of native species and age classes that consume less water, such as xeric tree species that may be drought tolerant and less vulnerable to insect outbreaks (Creed et al., 2014; Perry et al., 2015; Vose et al., 2016; Grant et al., 2013; Sun and Vose, 2016); 2) Use seedlings and saplings to increase tree survival after planting, for example saplings grown in gravel, and nursery containerized stock.

4.6.2. Approach 5.2: Enhance the ability of systems to retain water

Enhancing water storage and slowing the physical movement of water across the landscape increases the residence time of water, providing sources of water for plant transpiration, soil-water and plant-water storage, and seepage to groundwater (D'Odorico and Porporato, 2004). Water retained in forested systems is typically high-quality, clean, cold water that is slowly released throughout the year, a process likely to become even more important to natural resource managers seeking to sustain water quality and yield as the climate warms and seasonal precipitation becomes more variable. Climate changes to the hydrologic cycle are expected to challenge the capacity of forests to sustain delivery of water throughout the growing season and in dry periods; and also challenge forested systems' capacity to buffer and attenuate flood flows during more frequent extreme events (Capon et al., 2013; Perry et al., 2015; Garssen et al., 2017). Critical watershed recharge and storage areas include headwaters, vernal pools, transitional areas, riparian and bottomlands, floodplains, leaf litter and porous soils (Brooks, 2009). Planning to avoid or minimize disturbances in these areas may help to maintain the mechanisms that capture, absorb, and store water as land-use and climate continue to change. *Examples of adaptation tactics are*: 1) Thin forests to reduce stocking densities, and perform shorter harvest cycles to reduce interception and transpiration and increase water retention in forested systems. (NRC, 2008; de Jong, 2016; Vose et al., 2016); 2) Restore in-stream complexity by adding meanders, depressions and scour pools using natural stream channel classification (Rosgen, 1994, 2007) and restoration techniques (Yochum, 2017) to increase water retention in-channel (Williams et al., 2015).

4.6.3. Approach 5.3: Adjust systems to cope with increased water abundance, and high water levels

The Midwest and Northeastern regions are projected to receive increased annual precipitation, though the increases may be concentrated within certain seasons or may occur as a result of extreme events. Some sites may experience higher peak flows, increased flooding, and increased duration and frequency of soil saturation and inundation (Melillo et al., 2014). Increased water saturation and inundation can alter soil structure, vegetative and aquatic species diversity and assemblages (Laizé et al., 2017; Horne et al., 2017), nutrient availability, biomass production (Poff and Zimmerman, 2010; Capon et al., 2013; Perry et al., 2015; Garssen et al., 2017), and affect habitat suitability (Swanston et al., 2018). Using best management practices to account for increased saturation and inundation may enhance the capacity of the system to stabilize stormflows, maintain habitat, and avoid downstream water quality degradation due to erosion and nutrient runoff (Seavy et al., 2009; Perry et al., 2015). Retaining or introducing desirable species able to cope with saturated conditions may foster continued vegetated conditions and a competitive advantage over invasive species capitalizing on disturbance (Garssen et al., 2017; Perry et al., 2015). *Examples of adaptation tactics are*: 1) Manage riparian areas to include a diversity of species and genotypes, favoring future-adapted native species tolerant to saturated conditions or adapted to high water levels such as obligate wetland plants (Perry et al., 2015); 2) Target invasive species control in newly flood-prone areas to retain or recruit desirable riparian species.

4.6.4. Approach 5.4: Respond to or prepare for excessive overland flows (surface runoff)

Overland flows occur when soils cannot absorb water, such as when rain or meltwater flows over saturated soils, or as a result of rain intensity that is too high for vegetation and soils to absorb (Dunne and Leopold, 1978). Even modest changes in precipitation can amplify the magnitude and volume of overland flows and cause rapid changes in surface water levels following rain events. The initiation acceleration of water movement is largely controlled by the intensity of rainfall or snowmelt combined with site characteristics such as slope, vegetation density, soils, antecedent moisture condition, and land-use. Higher water velocity increases risk of soil erosion, particularly on wet or steep slopes, which can degrade water quality and aquatic habitat (Zimmermann et al., 2014). A suite of best management practices for reducing overland flow may include actions to increase surface roughness and canopy interception, maintain soil porosity, and otherwise disperse concentrated or fast-moving flows of water. Planning to anticipate and reduce overland flow sources is particularly important in areas prone to erosion, adjacent to infrastructure, and subject to early and rapid snowmelt over frozen soils. *Examples of adaptation tactics are*: 1) Strategically place downed wood to deflect, slow and pool overland flow water as snow melts over saturated soils and frozen soils; 2) Use wattles and water bars to slow overland flow water velocity and increase retention and recharge into soils.

4.7. Strategy 6: Design and modify infrastructure to accommodate future conditions

This strategy addresses actions for adapting infrastructure in forested watersheds, such as roads, skid trails, recreation trails, road-stream crossings, bridges, culverts, dams and other facilities associated with development. Infrastructure and transportation systems designs to avoid structural losses and damages by taking into account storm events and return periods documented in regional historical records (Perica et al., 2013). A changing climate may necessitate critical evaluation of past design concepts and criteria to minimize risks and safety concerns over the designed lifespan of the unit (Kilgore et al., 2016; Douglas et al., 2017; Wilhere et al., 2017; Milly et al., 2015). Roads, skid trails, road-stream crossings, recreation trails, facilities, and other infrastructure are known to affect local landforms and hydrology, particularly where impervious surfaces concentrate water into flow pathways, generating high-velocity runoff and erosion (Croke and Mockler, 2001; Wemple et al., 2017; 2001). Added considerations in design may be necessary to accommodate altered hydrology and reduce risks of damage, failure or total loss. These considerations may be especially important near high-risk areas and where the consequences of lost infrastructure are unacceptable (Furniss et al., 2010; Williams et al., 2015; Peterson and Halofsky, 2017).

4.7.1. Approach 6.1: Reinforce infrastructure to meet expected conditions

Shifts in landscape-level hydrology associated with climate change may pose risks to some facilities and infrastructure. Infrastructure and facilities are designed using historic hydrologic datasets to determine sizing and placement of units that meet access and safety criteria over a designed life-span (e.g. 25–100 years) (Maher et al., 2015). However, current infrastructure will be subjected to conditions that exceed historical norms (Milly et al., 2008), placing some facilities and structures at risk (Kilgore et al., 2016; Wilhere et al., 2017). Considering potential changes to hydrology due to climate change may help inform structural reinforcements and safety enhancements that reduce risks (Furniss et al., 2010; Strauch et al., 2015; Williamson et al., 2016; Peterson and Halofsky, 2017). Current aged, undersized, and poorly maintained structures are likely to require additional effort to cope with the challenges of extreme heat on surfaces, heavy storm events, high water levels, increased winter soil moisture and extreme events (Strauch et al., 2015; Daniel et al., 2017). Planning and design that reduces risk of infrastructure failure may also benefit biologic integrity and other water quality and aquatic habitat goals (Williams et al., 2015; Peterson and Halofsky, 2017). *Examples of adaptation tactics are*: 1) Replace undersized culvert with bottomless culvert using the stream simulation design to allow for sediment and debris to safely pass during higher flow events (USDA-FS, 2008; Barnard et al., 2015; Yochum, 2017); 2) On low-volume roads or trails convert culvert to a low-water crossing structure (ford or low-water bridge) designed to be overtopped (Clarkin et al., 2006).

4.7.2. Approach 6.2: Reroute or relocate infrastructure, or use temporary structures

Infrastructure located in areas prone to high soil-moisture and flooding may require repeated maintenance and other investments to maintain access and function as extreme precipitation events become more common; this is especially true for heavily trafficked systems such as roads, bridges, trails, and campsites (Strauch et al., 2015; Peterson and Halofsky, 2017). Structures unable to convey adequate high or low water flows often disconnect and fragment aquatic organism communities (Ficke et al., 2007). The physical relocation of necessary infrastructure and facilities away from high-risk areas may improve the quality of habitat adjacent to water resources and forested areas (Daigle, 2010). Using flexible temporary infrastructure (e.g. temporary bridges) can minimize long-term risks associated with permanent structures while still meeting near-term goals. The rerouting, or relocation of heavily accessed infrastructure away from unstable slopes or water resources to areas may reduce long-term maintenance costs and structural losses (Strauch et al., 2015; Keller and Ketcheson, 2015). *Examples of adaptation tactics are*: 1) Relocate campground facilities out of floodplains and away from dynamic surface waters to reduce hazards associated to flooding, or eroding streambanks (Peterson and Halofsky, 2017); 2) Reroute trails away from waterways with the high flood risk or potential, to areas with high drainage efficiency and deep-rooted vegetation (Strauch et al., 2015).

4.7.3. Approach 6.3: Incorporate natural or low impact development into designs

Infrastructure is often designed to efficiently drain water, by concentrating and diverting water flows to adjacent vegetation, ditches, surface waters, wetlands or stormwater systems. More frequent, intense, and heavy precipitation may result in excessive stormwater runoff. Concentrated stormwater runoff can cause adjacent areas to erode, and flood, destabilize stream channels, and impair water quality (Pyke et al., 2011; Ahiablame et al., 2012; Augustyn and Chou, 2013). Natural and low impact development techniques help to reduce stormwater conveyance, enhance groundwater recharge, and improve water quality by decentralizing flows and using soil and plants to capture and filter pollutants (Dietz, 2007; Pyke et al., 2011; Ahiablame et al., 2012; Kirshen et al., 2015). This approach may be especially effective in areas with high percentages of impervious land cover and sensitive ecosystems. *Examples of adaptation tactics are*: 1) Incorporate permeable surfaces into designs such as block pavers, porous asphalt and concrete to reduce hardening of surfaces and to increase infiltration of storm flows; 2) Attenuate and treat stormflows in depressional areas, using bioretention systems to capture runoff, recharge groundwater, and reduce pollutant loads (Ahiablame et al., 2012)

4.7.4. Approach 6.4: Remove infrastructure and readjust system

Facilities requiring substantial investments to maintain safety over the life-span of the system, or those posing human or ecological hazards, may become increasingly challenging to maintain as the climate changes. Removing or decommissioning infrastructure is a practical adaptation response (Furniss et al., 2010; Peterson and Halofsky, 2017). Decommissioning roads by ripping the roadbed and decompacting soils has been shown to increase hydraulic conductivity of soils, enhance water retention, and reestablish subsurface drainage to groundwater stores (Switalski et al., 2004). Readjusting the system can potentially improve water quality, decrease soil erosion, reduce overland flows and peak flows due to less impervious surfaces, and increase habitat quality by removing physical obstructions to wildlife connectivity. *Examples of adaptation tactics are*: 1) Decommission and revegetate unnecessary roads or trails that have high risk and low access (Strauch et al., 2015); 2) Decommission infrastructure to preferentially allow expansion of floodplain and migration of stream channel.

5. Adaptation demonstration projects

Testing the Forested Watershed Adaptation Menu with the Adaptation Workbook in planning workshops generated 22 adaptation demonstration projects. Adaptation demonstrations are examples of organizations applying this process to their real-world natural resource management projects and generating explicit adaptation tactics that align with their objectives. More than 250 adaptation demonstration projects have been generated using other adaptation menus (Swanston et al., 2016; www.forestadaptation.org). We provide two examples of adaptation demonstration projects that tested the Forested Watershed Adaptation Menu.

5.1. Demonstration project: Crowningshield conservation area habitat restoration project

Trout Unlimited New England, Franklin Land Trust, and the Massachusetts Department of Conservation and Recreation formed the Crowingshield project team, and collaboratively implemented a series of actions to help riparian forests and cold-water streams adapt to climate change within the North River watershed (spanning Vermont and Massachusetts). The team used the Adaptation Workbook to consider how climate change could affect the area. They then identified stream restoration actions on two properties that would achieve their conservation goals for maintaining high-quality, coldwater habitat into the future (www.forestadaptation.org/tu-ne).

5.1.1. Define location, project goals and objectives, and time frames

The North River Watershed covers 24,000 ha of land, which is primarily forested (83%) and includes 310 km of streams. Several property owners worked on this project, including the H.O. Cook State Forest managed by the Massachusetts Dept. of Conservation and Recreation and privately owned parcels conserved through the Franklin Land Trust. The parcels consist of primarily northern hardwood forest with areas of lowland hardwood and conifer forest. Areas near streams tend to have steep slopes and narrow valleys, and have been identified as coldwater fishery resources. All land owners and professionals participating in this landscape-scale project shared common strategic interests that span their individual management goals and objectives, including: (1) maintaining healthy and productive forests; (2) maintaining and improving the integrity of the watershed; (3) improving habitat and stream connectivity to benefit trout and other aquatic organisms, and (4) enhancing the ability of the watershed to cope with extreme precipitation events.

5.1.2. Assess site-specific climate change impacts and vulnerabilities

The project team combined broad-scale information from regional assessments of forest vulnerability to climate change (Janowiak et al., 2018; 2014) with their knowledge of the local landscape to identify characteristics of the area that they believed would increase or decrease risks from climate change. The location was identified as being most vulnerable to altered precipitation regimes across seasons an impact that posed the greatest risks to maintaining ecosystem functions. In particular, the project team were concerned about altered winter precipitation conditions (including reduced snowfall, and more frequent rain-on-snow events), and longer warmer growing seasons leading to reduced water levels and moisture stress later in the growing season. Additional concerns related to the impacts of more frequent intense heavy rain and extreme storm events that produce high velocity streamflow, reduce soil-water infiltration, and can result in streambank erosion. Many tributary streams and road crossings were viewed as vulnerable to extreme rain events because these areas had been affected by past storms. Climate-related declines in northern tree species and enhanced stressors such as forest pests and invasive species were identified as factors that may increase risks to forests and riparian areas. The valley type and sheltered nature of some locations may keep some areas buffered from warming temperatures. Overall, the project team determined the project areas to have moderate-high vulnerability to climate change by end of century.

5.1.3. Evaluate management objectives given projected impacts and vulnerabilities

The project team used the Adaptation Workbook to explore opportunities and challenges to meeting the property and water resource management objectives given changing conditions. The most concerning climate-related management challenges were based on the vulnerabilities identified in the previous step. For example, rising temperatures, particularly in summer months will reduce the water quality of aquatic habitats and reduce thermal refugia for the temperature-sensitive fish like brook trout, mottled sculpin, dace, and darters that the project team hoped to promote. More frequent and intense precipitation events threaten local infrastructure, and create challenges for the long-term management of aquatic habitat. More frequent and larger rain events leading to increased streamflow may exceed the hydraulic capacity of some undersized and aged culverts and stream crossings, resulting in erosion, channel instability, or even failure of the structure. Events resulting in "flashy" high velocity streamflow can reduce aquatic habitat quality by dislodging and dispersing large woody material downstream, and alter stream stability over-time. Adjacent riparian areas dominated by hemlock are at risk of pest infestation by the hemlock woolly adelgid as the pest expands its range northward with rising temperatures. Declines in hemlock and other northern conifer species are expected to negatively affect water quality if reduced forest cover allows water temperature to rise. However, tree mortality may provide opportunities to increase natural wood additions into streams and enhance riparian forest diversity through the management of underrepresented tree species. Although climate change creates significant challenges, the pr determined that their goals for improving aquatic habitat conditions were feasible in the near and long-term and did not warrant substantial modifications to address climate change. However, they also recognized that some of the goals associated with preserving cold-water aquatic habitat would become more challenging and may require more investment to maintain by end of century.

Table 2

Selected adaptation actions identified by management area location, for the Trout Unlimited adaptation demonstration in Vermont and Massachusetts, USA.

Location	Adaptation menu approaches	Adaptation tactics
Within stream channels	1.3: Maintain and restore stream channel form and function	Place large woody material into streams to improve habitat structure, increase stream complexity, and maintain coldwater refugia Select and cut trees from adjacent riparian areas that are at-risk from climate change and other stressors to be used for in-stream wood additions.
Stream bank	2.3: Reduce soil erosion and sediment deposition	Construct log-jam and use wood additions to stabilize highly-erodible stream banks (Yochum, 2017)
Riparian forest	3.1: Maintain or restore forest and vegetative cover in riparian areas 3.3: Maintain or improve the ability of forests to resist pests and pathogens 4.1: Favor or restore native species that are expected to be adapted to future conditions	Harvest selected trees within riparian areas to reduce the abundance of hemlock and other at-risk species and increase species diversity. Promote the growth and establishment of conifer and hardwood species that are expected to persist in the future (Janowiak et al., 2018), such as white pine.
Infrastructure at road-stream crossings	6.1: Reinforce infrastructure to meet expected conditions	Inventory and evaluate all crossings for competency of passing a 100 yr storm, and evaluate failure risk. Replace undersized culverts with more appropriately-sized culverts, arches, or bridges to accommodate larger flows, reconnect coldwater habitat, and improve aquatic organism passage.
	6.3: Incorporate natural or low-impact development into designs	Removed aged and failing culvert on low-use road. Replace with reinforced ford that allows for occasional vehicle access.

5.1.4. *Identify adaptation approaches and tactics for implementation*

The project team devised tactics (Table 2) that focused on their concerns related to in-stream dynamics and riparian vegetation described in Steps 2 and 3, and then articulated the broader intent of their actions by linking them to approaches from the Forested Watershed Adaptation Menu (Table 1). They were somewhat more concerned with in-stream vulnerabilities, which is reflected in the number and specificity of their tactics. Selection of adaptation strategies that restore channel form and function, reduce soil erosion, favor future adapted riparian forests resilient to pests, and redesigning infrastructure to accommodate projected hydrologic change, reflected their desire to accommodate change to ensure cold-water habitat will persist into the future. Although many of the tactics are recognizable as actions currently promoted as best management practices for stream restoration and forest stewardship, it is important to note that these actions also intentionally address key risks from climate change. Other tactics that may appear more novel, such as planting species adapted to warmer climates are new additions to the portfolio of management actions considered by the project team in this project.

5.1.5. *Monitor and evaluate effectiveness of implemented actions*

The project team, with the assistance of Cole Ecological Inc. and Antioch University New England identified monitoring items that would help evaluate the effectiveness of the adaptation tactics selected for implementation. The monitoring plan will help the team characterize alterations in channel-morphology, water quality, fluvial processes and habitat prior to and post-restoration activities. For example, the plan outlines efforts to monitor in-stream temperature for two years post-restoration; measure sediment deposition in the fall and spring; conduct annual macroinvertebrate surveys to monitor habitat establishment and aquatic health; and conduct inventory surveys of fish, aquatic organisms and forests for two years prior to and post-restoration.

5.2. *Demonstration project: Knife River forest improvement project*

Staff from the Minnesota Department of Natural Resources and the University of Minnesota-Duluth formed the Knife River project team, and collaborated to address the impacts of forest health and climate change on a property adjacent to a high-quality trout stream. This property lies in the northern headwaters of the Knife River watershed on Minnesota's North Shore of Lake Superior. The team used the Adaptation Workbook to consider climate risks and devise adaptation tactics, choosing strategies and approaches from the menu to connect management actions to their broader climate adaptation intentions.

5.2.1. *Define location, project goals and objectives, and time frames*

Located in the northern headwaters of the Knife River, the 145-ha project area contains the only naturalized wild steelhead trout population in Minnesota. The project parcel contains 2.5 km of the West Branch Knife River with no natural barriers preventing fish migration. The parcel is on state-owned lands that have been set aside as Minnesota School Trust Land, where forests are managed to generate revenue for the Permanent School Fund. Forest cover on-site primarily consists of paper birch (*Betula papyrifera*), bigtooth aspen (*Populus grandidentata*), other hardwoods, and balsam fir (*Abies balsamea)*. Management goals were to sustainably manage timber to generate revenue for the Permanent School Fund, and to protect water quality. Stands throughout this parcel have declined in recent years largely due to age-related succession of paper birch and aspen. Spruce budworm (*Choristoneura fumiferana*) outbreaks have occurred on balsam fir stands and other forest health issues are present. Primary project objectives in the following 5 years included responding to forest health concerns and maintaining forest cover, particularly conifer cover.

5.2.2. *Assess site-specific climate change impacts and vulnerabilities*

Information on the potential climate change effects and vulnerability of forests in Northern Minnesota (Handler et al., 2014) was used to identify potential climate related risks to forests on this property. The team used their knowledge of this parcel to identify how larger-scale projections may interact with on-site biophysical characteristics to aggravate existing forest health issues and accelerate water quality degradation. For example, shallow, rocky soils with relatively low soil-water field capacity are a dominant site characteristic, meaning that snow strongly influences aspects of the hydrologic regime such as soil moisture and stream temperature. Increased warming is projected to contract the duration of winters, which may alter the frequency of winter freeze-thaw cycles, increase frequency of rain-on-snow events, and reduce seasonal snowpack depth and retention. The team determined changes in precipitation and snowmelt represented the greatest climate change related impacts to site hydrology, and may result in more frequent overland flows. Overland flows can initiate or aggravate erosion, and were identified as immediate and long-term risks for this site. Some boreal species on-site are projected to lose suitable habitat by end of century (Handler et al., 2014). Longer growing seasons likely to increase forest pest life-cycles and pathogen infestations were also considered long-term risks for this site.

Table 3
Selected adaptation actions by management area location, identified for the Knife River adaptation demonstration, in Minnesota, USA.

Location	Adaptation menu approaches	Proposed adaptation actions
Site-wide	3.6: Enhance species age classes and structural diversity in forests	Harvest 70 ha (scheduled for 2018) to regenerate paper birch and aspen, reserving all white pine yellow birch, cedar, tamarack, black spruce and white spruce below 9-inch diameter limits.
	1.1: Maintain and enhance infiltration and water storage capacity of forest soils	Harvest and retain key species on-site to improve soil conditions, and buffer risks related to changing precipitation patterns and extreme events.
	3.2: Promptly revegetate areas after disturbance 4.1: Favor or restore native species that are expected to be adapted to future conditions	Accelerate timing of plantings post-harvest (scheduled 2019). Plant a diverse mix of native species and species expected to be adapted to future conditions.
	5.4: Respond to or prepare for excessive overland flows (surface runoff)	Prior to seedling establishment and growth on-site, use strategically retained conifers to shade snow that may reduce the rate and timing of snowmelt. Use coarse woody debris to deflect and intercept snow melt to reduce erosion of open sites and reduce delivery of turbid waters to river.
Wetlands	5.2: Enhance the ability of systems to retain water.	Increase riparian area management areas, reserving a larger areas around wetlands and seasonal pools.

5.2.3. Evaluate management objectives given projected impacts and vulnerabilities

After defining important site-level impacts and vulnerabilities, the team evaluated the long-term feasibility of meeting the state mandate to manage this parcel for economic output through sustainable forestry, and the provision of clean water through the end of century. Climate changes (identified in Step 2) pose risks for the management of this site and may worsen site hydrology over time, and likely exacerbate erosion. Additionally, the team judged that warming winters posed the largest risk to achieving goals in the short- and long-term. Past forest health issues have created gaps in the canopy that have exposed the forest floor to greater wind and solar radiation, influencing snowmelt timing and overland flows. Yet, these risks present opportunities for the team to achieve goals by focusing on management of disturbed areas to enhance productivity and maintain function even as boreal species decline. The team determined property-wide goals were feasible into the long-term, but would require added focus and attention in the near-term.

5.2.4. Identify adaptation approaches and tactics for implementation

The team were most concerned with projected changes in the site's snow-driven hydrology and the associated potential for an increase in erosion (decrease in water quality), which was reflected in their choices of strategic approaches to adaptation (Table 3). Selection of strategies and approaches that enhance the ability of forest soils to infiltrate water and reduce overland flows reflected their focus on retaining water on-site given projected regional climate impacts and site vulnerabilities. Likewise, their choice of strategies to enhance the diversity of the age and structure of the forest, along with strategies to favor species adapted to future climates, reflected willingness to adjust species composition and forest structure to reduce risks to the water resource. The tactics that supported these approaches focused on adjustment of riparian, wetland, and upland vegetation to support increased infiltration, longer snowpack duration, and decreased overland flow. The team identified tactics that align with their current management practices, but have added relevance given climate changes. They also developed tactics that they considered "new ideas" to help meet climate-related challenges. These tactics were created to deliberately prepare the system to cope with variable precipitation, more frequent overland flows, and warming, ideally reducing risks to vegetation and enhancing on-site water retention. A 70-ha portion of the stand has been scheduled for harvest in 2018, and a diverse mix of native species expected to be adapted to future conditions will be planted in 2019.

5.2.5. Monitor and evaluate effectiveness of implemented actions

The team are collaborating with the University of Minnesota-Duluth to define a monitoring plan that measures the effectiveness of forest management actions, beginning in 2018–2019. Monitoring plans are to observe site productivity and retention of snow over time by conducting vegetation surveys to evaluate forest regeneration post-harvest, and snow cross surveys to evaluate snow depth and snow-water equivalent. Additional water quality observations will evaluate turbidity associated with overland flows and soil loss.

6. Concluding remarks

The Forested Watershed Adaptation Menu collates, tiers, and summarizes a myriad of strategies and approaches that are otherwise spread widely through the literature and often inaccessible to practitioners. The combination of the Adaptation Workbook process and Menu helps practitioners translate broad adaptation concepts into implementable actions and ensures that the intentions of those actions are explicitly identified. The menu serves the purpose of providing a relatively concise platform of adaptation ideas relevant to different resource areas, and can help launch or expand discussions that can be as much about values and risk tolerance as they are about practices. These discussions are of course not as easily quantified or characterized as adaptation demonstration projects (Janowiak et al., 2014; Ontl et al., 2018), but we suggest they are an important component in the evolution of communities of practice in this era of climate change.

Conflicts of Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2019.01.005.

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