OPTIMIZING RIPARIAN FOREST BUFFER IMPLEMENTATION FOR CLIMATE ADAPTATION AND RESILIENCE



Prepared for:
Chesapeake Bay Program
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The project, proposed by the Forestry Workgroup, provides information and guidance for government officials and practitioners to increase riparian forest buffer (RFB) implementation to support climate adaptation and resilience. Chesapeake Conservancy was contracted to complete the project, which began in the fall 2023 and ended May 2025.

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Cover photo by Will Parson/Chesapeake Bay Program

STEERING COMMITTEE

In addition to the Forestry Workgroup, a steering committee provided valuable guidance for the project (Table 1).

TABLE 1 PROJECT STEERING COMMITTEE

Technical Lead	
Robbie Coville	Pennsylvania Department of Conservation and Natural Resources
Contractor	
Carly Dean	Chesapeake Conservancy
Ryan Hill	Chesapeake Conservancy
Michael Augustin	Chesapeake Conservancy
Steering committee	
Lydia Brinkley	Upper Susquehanna Coalition
Jamileh Soueidan	NOAA, Chesapeake Bay Program
Meghan Noe Fellows	Delaware Center for the Inland Bays
Susan Minnemeyer	Nature Plus
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Background

The benefits of riparian forest buffers (RFBs) to water quality are well-known and are reflected in the very ambitious goals set for riparian forest buffer restoration in the Chesapeake Bay Watershed Agreement and state Watershed Implementation Plans. A wealth of information on other critical RFB benefits for climate adaptation, such as storm events and flooding, fish, wildlife and plant life and water supplies is also available but less discussed and analyzed. This project synthesizes compelling information on the climate adaptation benefits of RFBs through this synthesis report and an interactive StoryMap supported by locally relevant case studies.

OUTCOMES

The priority audiences for the project deliverables are state/local government officials and practitioners. The project aims to increase RFB implementation to support climate adaptation and resilience. Outcomes include:

- A synthesis of available information on climate adaptation benefits of RFBs
- Identification of options to maximize the climate adaptation of RFBs (e.g., through project siting, species selection, etc.)
- Opportunities to improve the resilience of RFBs to a changing climate; and
- Characterization of RFB restoration priority areas and conservation opportunities based on where RFBs will provide the greatest climate adaptation benefits and making this characterization available for practitioner use.

METHODS

The CBP Forestry Workgroup proposed this project. The GIT Technical Lead provided ongoing project oversight, key guidance and feedback and assisted in stakeholder engagement.

Individuals were invited to the steering committee as representatives of local and state governments, practitioners and resource experts. This group provided valuable guidance and examples on how to better use RFB plantings to improve communities' resilience to climate change.

Next, Chesapeake Conservancy researched and synthesized information into this synthesis report. The synthesis report is accompanied by an annotated bibliography and an interactive ArcGIS StoryMap to communicate the climate adaptation benefits of forest buffers and options for maximizing climate adaptation benefits or resiliency through project siting and design.

Impacts of a changing climate on the Chesapeake

The Chesapeake climate is changing. In 2021, all 33 climate divisions in the watershed experienced statistically significant increases in average air temperature compared to the period from 1901 to 2000 (Chesapeake Progress, 2024). By the end of the century, temperatures in the Mid-Atlantic region are projected to increase on average by 5.27 – 9.11°F (Brooks, Norman, & Kreye, 2024). Many models predict that over the next century, intense precipitation events will continue to become more frequent in the Mid-Atlantic (Butler-Leopold P. R., et al., 2018). Precipitation patterns are also expected to change, (Brooks, Norman, & Kreye, 2024), with increases expected in winter and spring and the potential for long periods of drought in summer and fall (Butler-Leopold P. R., et al., 2018; Modi, Fuka, & Easton, 2021; Maryland Department of the Environment, 2021). Hardiness zones—the standard developed by the U.S. Department of Agriculture used to determine which plants are most likely to survive at a location—have shifted from 2012 to 2023 in many areas across the watershed. (Agricultural Research Service, U.S. Department of Agriculture, 2023), impacting both native and invasive species.

The impacts on near- and in-stream environments—as well as the ecosystem services they provide—could be substantial.



FIGURE 1 A MATURE RFB IN QUEEN ANNE'S COUNTY, MD. CREDIT: WILL PARSON/CHESAPEAKE BAY PROGRAM

INCREASED STORM EVENTS AND FLOODING

The effects of a changing climate are projected to increase the frequency and intensity of storms (Palmer R. N., Nislow, Ericson, & Backiel, 2019). These storm events will impact communities by affecting the magnitude of flood peak, the time to issue flood warnings, and rates of stream bank erosion, among other consequences. Total precipitation is projected to increase by approximately 10% by the end of the 21st century (Modi, Fuka, & Easton, 2021).

THREATS TO FISH, WILDLIFE, AND PLANT LIFE

The cumulative impacts on fish, wildlife, and plant life across the Chesapeake Bay watershed are particularly concerning because many species are already at the edge of their temperature range (NOAA, 2024). Surface water temperatures are expected to rise due to warming air temperatures (Marvel, et al., 2023; Welsch, 2017) in addition to heated stormwater runoff and research is already showing northward shifts in species ranges (Batiuk R. B.-N., 2023). Many invasive species and insect pests will increase or become more damaging (Vose, et al., 2018).

CHANGES TO WATER SUPPLY

Surface and groundwater supplies in many areas of the Chesapeake are expected to experience increased inputs of nitrogen (Bhatt, et al., 2023), largely due to the increase in precipitation. The seasonal availability of water supplies is expected to change along with changing precipitation patterns. Increased storm events may lead to increased erosion and lower the groundwater table while increased water temperatures may lead to increased evaporation of surface waters, further stressing water supplies. (Maryland Department of the Environment, 2021).

Threats to communities and benefits provided by RFBs

Riparian forest buffers (RFBs) can help mitigate the projected impacts of a changing climate and help communities and ecosystems adapt to a changing climate. Specifically, RFBs can reduce the following impacts of climate change:

- Increased storm events and flooding
- Threats to fish, wildlife, and plant life
- Changes to water supplies
- Additional threats to communities

Increased storm events and flooding

The effects of a changing climate are projected to result in an increase in more frequent and intense storms (Palmer R. N., Nislow, Ericson, & Backiel, 2019). These storm events will impact communities, affecting the magnitude of flood peak, the time to issue flood warnings and rates of stream bank erosion, among other consequences. Total precipitation across the Chesapeake region is projected to increase by approximately 10% by the end of the 21st century (Modi, Fuka, & Easton, 2021). Relative to 1995, mean annual precipitation across the watershed is expected to increase, with projected increases of 3.11% by 2025, 4.21% by 2035, 5.34% by 2045 and 6.91% by 2055 (Bhatt, et al., 2023). Increases in precipitation are not expected to be distributed equally throughout the year, with most of these increases expected in winter and spring (Butler-Leopold P. R., et al., 2018; Modi, Fuka, & Easton, 2021; Maryland Department of the Environment, 2021). Soil composition and vegetation density found in riparian areas can help mitigate the impacts of increased storm events and flooding by reducing flood peaks. These features also delay flood peaks, giving more time to issue flood warnings. Further, root systems in riparian areas can stabilize stream banks, reducing erosion and sedimentation.



FIGURE 2 STORM NEAR ASHBURN, VA. CREDIT: THOMAS CIZAUSKAS VIA FLICKR

Reducing flood peak

Flood peak is the highest value of the stage or discharge attained by a flood (Langbein & Iseri, 1960). Flood peaks are influenced largely by the volume and velocity of runoff delivered to waterways during and following storm events (Konrad, 2003).

In RFBs, dense vegetation can slow down flood waters and ultimately lead to a decrease in the volume (Broadmeadow & Nisbet, 2010) and velocity (Thomas & Nisbet, 2007) of runoff entering the channel by enhancing soil infiltration and water storage capacity. Flood mitigation benefits are likely to be greatest where RFBs replace land uses that promote rapid runoff (for example, where there is soil sealing and compaction on sensitive soils) (Broadmeadow & Nisbet, 2010). As newly planted buffers mature, the greater inputs of organic matter and the action of tree roots continue to improve soil structure (Broadmeadow & Nisbet, 2010) and provide enhanced flood mitigation benefits to the local area. Further, woody debris in the channel deposited by forests slows stream flows locally (Broadmeadow & Nisbet, 2010; Dixon, 2016).



FIGURE 3 FLOOD DAMAGE IN OWEGO, NY. CREDIT: CHRIS WAITS VIA FLICKR

Giving more time to issue flood warnings

Advanced notice to communities in the event of a flood can save lives and reduce economic losses (EASPE, Inc., 2022). After one of the most devastating storm events to hit the Chesapeake region—Hurricane Agnes in 1972, which resulted in 122 fatalities (Chesapeake Bay Foundation, 2022)—regional flood warnings have greatly improved. In the future, as storm events continue to intensify and become more frequent, the size and frequency of river flooding will be amplified (Mallakpour & Villarini, 2015). Flood warnings deployed before a dangerous situation can help communities cope. Understanding the potential timing of a flood peak during a storm event will give authorities time to warn communities of the potential hazards and ensure enough time to prepare (Dixon, 2016; Palmer R. N., Nislow, Ericson, & Backiel, 2019).

Vegetation and soils are influential aspects of RFBs that help the system mitigate extreme rain events as compared to hardened surfaces and areas where forests are cleared to the edge of the stream. Soils in riparian forests have greater infiltration capacity (Eisenbies, Aust, Burger, & Adams, 2007) and water storage capacity which reduces surface runoff and delays the passage of rainwater to nearby waterways (Broadmeadow & Nisbet, 2010). In addition, a relatively high percentage of rainfall in riparian forests is lost to evapotranspiration—the process through which plants absorb water and release it into the air—and therefore does not contribute to stormflow (Broadmeadow & Nisbet, 2010). All of these RFB characteristics together can help reduce impacts to communities by desynchronizing the flood hydrograph and delaying the flood peak (Dixon, 2016; Palmer R. N., Nislow, Ericson, & Backiel, 2019; Thomas & Nisbet, 2007).

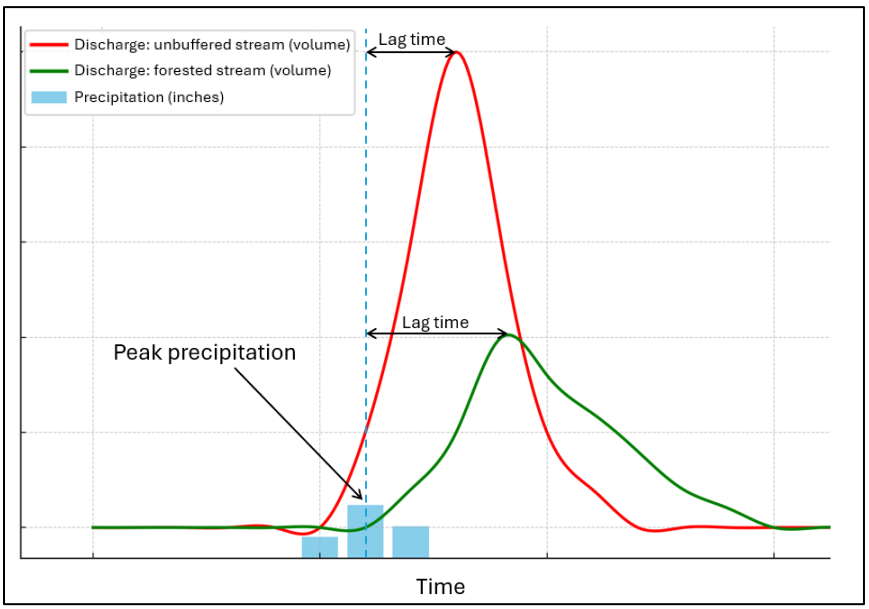


FIGURE 4 FLOOD HYDROGRAPH

Mitigating increases in bank erosion

Increases in the intensity and frequency of storm and flooding events could potentially increase erosion and sedimentation in small streams (Butler-Leopold, et al., 2018). As runoff initially moves downslope toward waterways, RFBs can help buffer and reduce sediment delivery from adjacent land before it enters creeks and streams (Broadmeadow & Nisbet, 2010). Additionally, plant roots stabilize and strengthen riverbanks, reducing bank erosion and sedimentation (Broadmeadow & Nisbet, 2010). Bank erosion has impacts on the concentrations of nutrients in groundwater as well. Riparian forest buffers along deeply incised streams are higher up on the bank than the stream level—sub-surface groundwater bypasses the root system and the nutrients it carries enters directly into waterways (Bentrup, 2008), making erosion prevention important for water supplies.

Threats to fish, wildlife, and plant life

Water temperatures are a principal variable impacting biological processes within streams and rivers (Dugdale, Malcolm, Kantola, & Hannah, 2018). From 1960 to 2014, the Chesapeake Bay region experienced an overall increase in stream water temperature (US Environmental Protection Agency, 2025). Riparian species are responding to increased water and air temperature as well as to changing precipitation patterns (Knouft & Ficklin, 2017). Plant species in the mid-Atlantic are experiencing a general northward shift in their ranges (USDA, 2023). In addition, invasive species, insect pests, and pathogens may increase or become more damaging (Butler-Leopold, et al., 2018). Riparian forest buffers are effective at moderating stream temperatures, can provide corridors and microclimate refugia to accommodate shifting species ranges, and native species in riparian forest buffers can provide resilience against invasive species and pests.

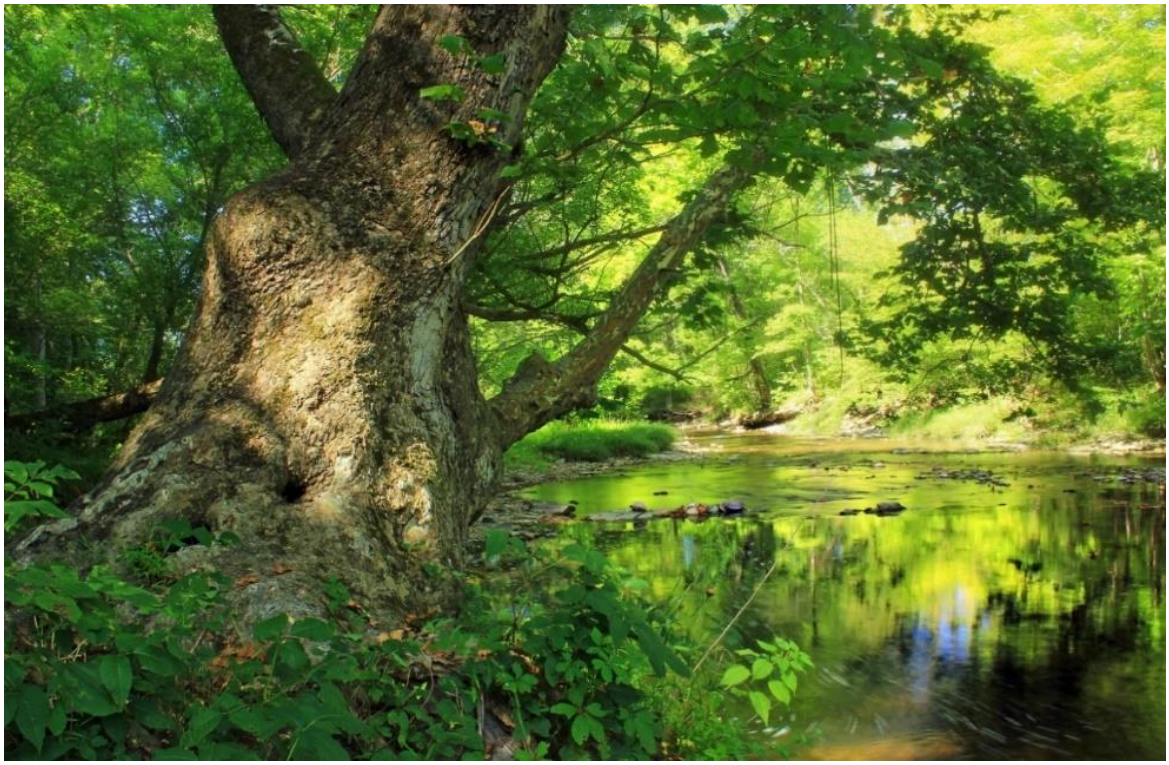


FIGURE 5 LARGE SYCAMORE ALONG HOKENDAUQUA CREEK, ALLEN TOWNSHIP, NORTHAMPTON COUNTY, WITHIN KREIDERSVILLE COVERED BRIDGE PARK. CREDIT: NICHOLAS A. TONELLI VIA FLICKR

Moderating stream temperatures

The U.S. Geological Survey maintains thousands of stream gauges across the United States. Across the Chesapeake Bay watershed, 69% of 129 gauges showed an increase in water temperature from 1960 to 2014 with the largest increases in the southern part of the region (US Environmental Protection Agency, 2025). Increased stream temperatures are largely due to heated runoff entering streams from impervious surfaces in developed areas (Batiuk R. B.-N., 2023). Increased summer temperatures in many river environments may reduce the thermal suitability for a range of freshwater fish species (Dugdale, Malcolm, Kantola, & Hannah, 2018). Temperature also alters species' behavior; for example, in fish, behavior changes such as the ability to migrate and extent of migration, metabolism and feeding, changing growth, fecundity, longevity and disease susceptibility can all be affected (Bowler, Mant, Orr, Hannah, & Pullin, 2012).

Warming water temperatures are especially concerning in the Chesapeake as many fish species have high cultural and economic significance (Batiuk R. B.-N., 2023). Shorter-term extreme heat events negatively impact aquatic habitats (Batiuk R. B.-N., 2023); however, temperature projections predict that when compared to non-vegetated buffers, riparian forest buffers may decrease the average number of days exceeding 80° F these high temperatures into the future by between 39.1% - 47% between 2030 and 2063 (Knouft, et al., 2021). While Brook Trout have a maximum thermal tolerance at 75° F (Albertson, Ouellet, & Daniels, 2018), negative impacts of increased water temperatures on potential food availability may also have a large impact on the ability of Brook Trout to thrive as streams become warmer (Albertson, Ouellet, & Daniels, 2018; Hitt, Rogers, & Kelly, 2024). RFB restoration should be maximized in coldwater watersheds (Batiuk R. B.-N., 2023) to help protect species vulnerable to increased water temperatures like Brook Trout.



FIGURE 6 BROOK TROUT IN CENTRAL PENNSYLVANIA. CREDIT: LOGAN STENGER, CHESAPEAKE CONSERVANCY.

RFBs naturally reduce stream temperatures by providing shade—particularly with maximum temperatures in spring and summer—by affecting the amount of solar radiation received by the stream (Bowler, Mant, Orr, Hannah, & Pullin, 2012; Batiuk R. B.-N., 2023), increasing evapotranspiration and facilitating infiltration (Batiuk R. B.-N., 2023). Habitat complexity caused by in-stream woody debris that creates deep pools in RFBs create cooler microclimates, providing refugia for sensitive species (Seavy, Gardali, Golet, Griggs, & Howell, 2009; Graziano, Deguire, & Surasinghe, 2022).

Accommodating shifting species ranges

As a result of changing local climate conditions, plant species ranges are expected to change, impacting their ability to support wildlife communities. A new version of the USDA's Plant Hardiness Zone Map whos northward trends in plant hardiness zones from 2012 to 2023 (USDA, 2023). Stream water temperatures are expected to warm (Knouft & Ficklin, 2017) which could change a species' range (Dugdale, Malcolm, Kantola, & Hannah, 2018).

The Climate Change Tree Atlas (Iverson, Prasad, Peters, & Matthews, 2019) modeled future changes in suitable habitat for 125 tree species across the eastern U.S. and projected declines for many northern and remnant boreal tree species as well as increases in suitable habitat for many southern and drought-resistant tree species (Butler-Leopold P. R., et al., 2018). Ecosystems that are limited to particular environments will have less opportunity to migrate (Butler-Leopold P. R., et al., 2018), making them less resilient to a changing climate. As a result of increasing stream temperatures, cold-water fish species may experience decreases in their distribution or range shifts to higher latitudes, while ranges of warm-water species may either expand or contract (Knouft & Ficklin, 2017).

The complex structure of RFBs provides habitat that offers a range of microclimate refugia (Bentrup, 2008). A network of intact buffer corridors can allow species to migrate as the conditions for suitable habitat (Bentrup, 2008; Graziano, Deguire, & Surasinghe, 2022) may shift northward (USDA, 2023). Riparian forest buffers deposit woody debris into streams, which can form deep-water pools where water is cool, providing refugia where water temperatures are increasing and drought stages last longer (Graziano, Deguire, & Surasinghe, 2022) and may support the migration of species to more suitable habitats.

Resilience against invasive species and pests

RFBs are particularly vulnerable to invasive species because they are often located between developed areas where invasive species are more present (Warnell, 2023). Many invasive species and insect pests in the Mid-Atlantic are expected to increase or become more damaging (Vose, et al., 2018; Butler-Leopold P. R., et al., 2018). Invasive species of concern that are expected to become more problematic include spongy moth, emerald ash borer and Asian long-horned beetle (Butler-Leopold P. R., et al., 2018) as well as ticks (Sonenshine, 2018). While spotted lanternfly is an invasive species of concern throughout the Chesapeake Bay Watershed, more work needs to be done to develop predictive models of spotted lanternfly spread based on climate and habitat suitability (Ladin, Eggen, Trammell, & D'Amico, 2023). Invasive plants of concern that will likely expand ranges northward as temperatures warm include kudzu (Hickman & Lerdau, 2013) and shrub and Morrow's honeysuckle (Johnson, et al., 2020) which are all commonly found in riparian areas in the Chesapeake.



FIGURE 7 EMERALD ASH BORER DAMAGE. CREDIT: USDA FOREST SERVICE, EASTERN REGION VIA FLICKR

Changes to water supplies

Across the Chesapeake, surface water (including rivers and streams) and groundwater provide drinking water to 18.5 million residents (Chesapeake Bay Program, 2025) and support approximately 21,000 square miles of farmland (Chesapeake Bay Foundation, 2025). Roughly 75% of people in the watershed get their drinking water from surface water sources (Solyst, 2021). Expected increases in precipitation and temperature will result in changes to the quality and availability of surface and groundwater. Models predict that by the end of the 21st century precipitation will increase by 10% in the Chesapeake region (Modi, Fuka, & Easton, 2021). Across the Mid-Atlantic region, models predict that air temperatures will increase on average by 5.27 – 9.11°F (Brooks, Norman, & Kreye, 2024). Precipitation patterns are also expected to change, impacting the seasonal availability of water supplies. More significant precipitation in winter and spring is predicted, with likely less in the summer and fall (Butler-Leopold P. R., et al., 2018; Modi, Fuka, & Easton, 2021). Riparian forest buffers can mitigate two of the major threats to water supplies: increases in nitrate in water supplies and surface and groundwater availability.



FIGURE 8 CREDIT: R. NIAL BRADSHAW VIA FLICKR

Mitigating increased nitrate in water supplies

Since the signing of the first Chesapeake Bay Agreement in 1987 (Casey, et al., 1987), nitrogen remains a top nonpoint source pollution concern across the watershed (Chesapeake Bay Program, 2025). Nitrogen makes its way into our water supply as components of runoff and groundwater flow (Welsch, 2017). Nitrogen is commonly found in waterways in the form of nitrate—a naturally occurring compound made of nitrogen and oxygen. Nitrate has already made drinking water supplies unsafe in communities throughout the Chesapeake. Increased nitrate levels can raise the risk of cancer, nervous system deformities in infants, hemorrhaging of the spleen and other problems (Solyst, 2021). Riparian areas have been shown to protect water quality for drinking waters (Vermont Agency of Natural Resources, 2005; Cole, Stockan, & Helliwell, 2020).



FIGURE 9 LOOKING EAST ACROSS THE MCMILLAN RESERVOIR IN WASHINGTON, DC. CREDIT: INTANGIBLEARTS VIA FLICKR

Largely due to increased precipitation and associated runoff, inputs of nitrogen into surface water is expected to increase under future scenarios. Models projecting future climactic characteristics predict a 2.6%–10.8% increase in nitrogen loads to the tidal Chesapeake Bay (Bhatt, et al., 2023). Rates of denitrification—the process by which biological activities remove nitrogen from watersheds and distribute it back into the atmosphere—are expected to slow in the Chesapeake (Bhatt, et al., 2023) which is especially concerning as denitrification is the primary process for permanently removing nitrogen from a buffer (Bentrup, 2008).

While increased nitrate concentration in drinking water increases treatment costs for water suppliers (especially in agricultural watersheds with high rates of runoff from agricultural fields (Wu, Khalid, Mitchell, & Ha, 2024), riparian forest buffers are widely considered one of the most effective conservation practices for managing nutrients (Washington, Groffman, Duncan, Band, & Miller, 2024). Plants in riparian areas take up nitrogen and store it in their biomass, reducing loads in waterways (Palone & Todd, 1997). However, plant uptake of nitrogen does not permanently remove nitrogen because it returns to the soil upon death and decay (unless the plants are harvested) (Bentrup, 2008). Buffers have been shown to effectively reduce nitrogen transport to surface waters and can remove nitrogen from groundwater (Schultz, Isenhart, & Simpkins, 2004; Washington, Groffman, Duncan, Band, & Miller, 2024), but this is only applicable where the water table is high or where shallow groundwater flows through or near the root zone (Palone & Todd, 1997; Welsch, 2017)

Supporting surface and groundwater availability

Increased air and water temperatures can result in increased evaporation rates and less water availability of surface water resources (Maryland Department of the Environment, 2021). Riparian forest buffers naturally reduce stream temperatures by providing shade (Bowler, Mant, Orr, Hannah, & Pullin, 2012; Dugdale, Malcolm, Kantola, & Hannah, 2018), potentially mitigating increases in evaporation rates.

Increases in atmospheric carbon dioxide can increase water use efficiency in plants, which could ultimately increase groundwater recharge (Modi, Fuka, & Easton, 2021; Washington, Groffman, Duncan, Band, & Miller, 2024). However, long periods of drought will lower stream flows and water availability during peak demand (Maryland Department of the Environment, 2021) especially in summer and fall when precipitation is expected to decrease (Modi, Fuka, & Easton, 2021). Riparian forest buffers can enhance groundwater recharge (Schultz, Isenhart, & Simpkins, 2004; Graziano, Deguire, & Surasinghe, 2022) which can help mitigate the effects of lower precipitation during times of drought.

Increased intensity and frequency of flooding events are expected to increase erosion of stream banks (Butler-Leopold P. R., et al., 2018), which can have the effect of lowering water table levels along streams (Gu, 2017 as cited in Washington et al., 2024). These lower water tables in riparian areas mean groundwater is less available for use while lowering rates of denitrification (Groffman et al., 2002 as cited in Washington et al. 2024). Plant roots in riparian forest buffers stabilize and strengthen riverbanks, reducing bank erosion (Broadmeadow & Nisbet, 2010) and may mitigate some of the impacts of storm events on groundwater recharge related to erosion.

Additional threats to communities and benefits of RFBs

- Algal blooms: Harmful algal blooms pose serious consequences for water supplies, fisheries, recreational uses, tourism, and property values; excessive nitrogen and phosphorus loading may cause blooms to reach larger magnitudes and persist longer (Paerl, Otten, & Kudela, 2018). Nitrogen loads to the tidal Chesapeake Bay are expected to increase by up to 10.8% (Bhatt, et al., 2023). However, riparian forest buffers have been shown to effectively reduce nitrogen transport to surface waters (Schultz, Isenhart, & Simpkins, 2004; Washington, Groffman, Duncan, Band, & Miller, 2024).
- Windbreaks: Riparian forest buffers can act as windbreaks (Braithwaite & Mallik, 2011), typically considered an agroforestry practice that helps with soil erosion control, livestock protection, wind protection, and snow control (Smith, et al., 2021).

- Heat refugia and recreation: Recreation-based activities like whitewater rafting, canoeing, and swimming are often concentrated within riparian zones (Graziano, Deguire, & Surasinghe, 2022). This is due in part to forests' cooler temperatures compared to nearby areas, especially in urban areas (Alliance for the Chesapeake Bay, 2004), which leads to the increased importance of forest cover for communities experiencing increased temperatures (Sinha, et al., 2021).

Summary: Threats to communities and benefits provided by RFBs

Riparian forest buffers provide a variety of benefits that address the primary and additional threats to communities referenced in this report. Benefits of RFBs are more extensive than listed here—this table is a first step to help practitioners understand how RFBs can address the threats specific to their communities.

TABLE 2. SUMMARY: FUNCTIONS OF RFBS AND THREATS TO COMMUNITIES ADDRESSED

	Threats to communities addressed			
Functions of RFBs	Increased storm events and flooding	Threats to fish, wildlife and plant life	Changes in water supplies	Additional threats
Intercept heated runoff, slow flood waters	●	●		○
Enhance soil infiltration, increase water storage, increase groundwater recharge	●	○	●	
Encourage denitrification, store nitrogen in biomass, reduce nitrogen delivery		●	●	●
Prevent bank erosion, reduce sediment delivery	●	●	○	○
Shade streams, moderate stream and riparian area temperatures		●	○	●
Create and support healthy habitat		●	○	○
Act as windbreaks, reduce soil erosion from land		○		●

● Substantial impact on threats

○ Co-benefit provided

Optimizing the benefits of RFBs and supporting RFB resilience

Riparian forest buffers are a key practice to help communities adjust to a changing climate (Chespeake Riparian Forest Buffer Network, 2024). Based on satellite imagery collected in 2017/2018, 68.85% of the riparian area throughout the watershed was forested; however, trends indicate a net loss in buffer coverage making it unlikely that the goal set in the *Chesapeake Bay Watershed Agreement* of 70% RFB coverage by 2025 will be met (Chesapeake Progress, 2024).

Through the end of the 21st century, lowland and riparian forests are expected to experience moderate impacts, have moderate adaptive capacity, and are moderately vulnerable compared to other forest types in the Chesapeake when evaluating differences in climate and responses to climate change (Butler-Leopold P. R., et al., 2018). As communities work to set and achieve RFB restoration, key siting and design principles should be considered for new plantings to optimize the benefits of RFBs. Riparian forest buffers themselves will be subject to the threats of increased storm events and flooding, threats to fish, wildlife, and plant life and changes to water supplies, affecting the health and vigor of the species. To reduce risks and ensure long-term benefits of RFBs, communities must consider how to incorporate climate change projections in buffer designs (Perry, et al., 2015). Siting and design considerations to address threats may also benefit RFB resilience.

Siting

Riparian Forest Buffers are key landscape features at the interface of land and waterways. The siting of RFBs along rivers and smaller tributary creeks and streams can provide varying benefits when considering communities upstream and downstream. Appropriate siting of RFBs should optimize synergies between both local and watershed-scale factors (Graziano, Deguire, & Surasinghe, 2022) and be tied to both current and projected future landscapes across the watershed. Siting considerations include the relationship between upstream and downstream communities, the impacts of adjacent and upslope land uses, and the importance of intact, continuous RFB corridors.

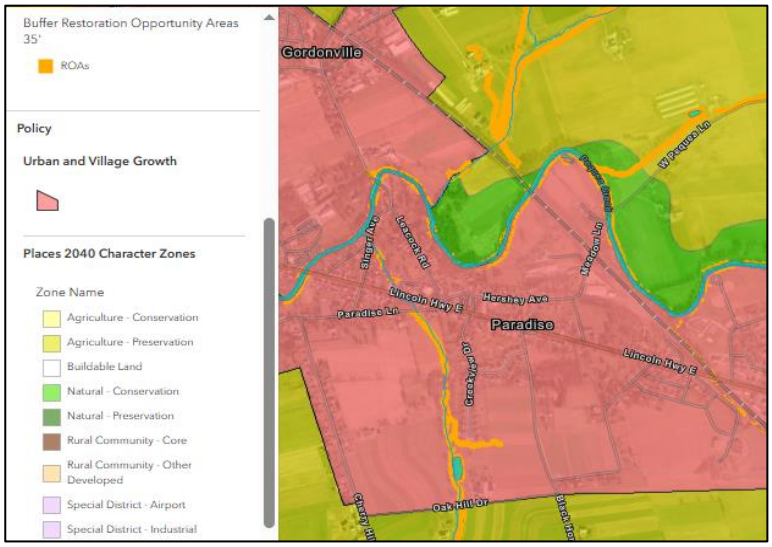


FIGURE 10 LANCASTER CO. BUFFER RESTORATION OPPORTUNITIES ARE CONSIDERED ALONGSIDE URBAN AND VILLAGE GROWTH ZONES. SOURCE: LANCASTER CLEAN WATER PARTNERS COLLABORATIVE WATERSHED MAPPING TOOL.

Upstream and downstream

Careful assessment of upstream landscape and stream channel characteristics can inform appropriate restoration strategies to mitigate impacts of increased storm events and flooding—this is especially true where upstream headwaters reaches are incised and confined (Thomas & Nisbet, 2007). While riparian forest buffers restoration projects have a multitude of local benefits, the slowing of water flow may cause water volumes to back up into upstream areas, resulting in flooding upstream (Palmer R. N., Nislow, Ericson, & Backiel, 2019). Protection of forests in the headwaters—both riparian and upslope—should be prioritized (Graziano, Deguire, & Surasinghe, 2022) to reduce the potential impacts from RFB restoration along downstream and mainstem reaches. This is a prime example of how downstream and upstream restoration strategies, as well as restoration and land conservation strategies, should be developed in conjunction with one another to optimize benefits and minimize negative impacts or vulnerabilities (Graziano, Deguire, & Surasinghe, 2022). When upstream communities are considering impacts to downstream communities, targeting RFBs in the upper and middle parts of a catchment can reduce the overall flood peak downstream (Dixon, 2016).

Connected riparian forest buffers provide refugia by keeping stream temperatures cooler and maximizing habitat diversity (Bentrup, 2008) allowing aquatic and terrestrial species to move upstream and downstream as they seek refugia from threats to fish, wildlife and plant life. For this reason, where possible it is valuable to expand riparian forest adjacent to existing RFBs rather than have many smaller and disconnected RFBs.

Adjacent, upslope land uses

Impervious cover can exacerbate the effects of increased heavy precipitation events in urban areas (Butler-Leopold P. R., et al., 2018). Therefore, RFBs can have the greatest benefits to address the effect of increased storm events and flooding when they replace impervious land uses on sensitive soils which promote rapid runoff due to soil sealing and compaction (Broadmeadow & Nisbet, 2010). To prevent erosion and sedimentation, areas with steep slopes and fine-textured soils should be prioritized for RFB restoration (Bentrup, 2008).

Stream temperature is influenced by a variety of environmental variables including patterns of upslope land use and topography (Dugdale, Malcolm, Kantola, & Hannah, 2018; Batiuk R. B.-N., 2023), as well as stream width, river discharge, and whether the stream is in the headwaters or lowlands (Bowler, Mant, Orr, Hannah, & Pullin, 2012). A main driver of warming stream temperatures is warmer runoff from upslope, developed areas, therefore, watersheds with low

forested cover and sparce riparian cover are particularly vulnerable to warming (Batiuk R. B.-N., 2023) and should be prioritized for restoration.

In places where nitrate runoff from upslope agricultural land is a concern, wider buffers may be needed to encourage intercept more runoff before it enters streams (Alliance for the Chesapeake Bay, 2004). Groundwater recharge areas are also important areas to restore RFBs and soil types could be considered (Bentrup, 2008). Landscapes with short connections between surface and groundwaters, for example in places with karst or limestone terrain are especially susceptible to water quality problems (Bentrup, 2008). Buffers around sinkholes and sinking streams can minimize polluted runoff entering directly into groundwater (Bentrup, 2008).

Intact, continuous corridors

Because riparian restoration may slow water flows downstream, there is a potential for floodwaters to back up in upstream areas, (Palmer R. N., Nislow, Ericson, & Backiel, 2019). Therefore, buffer restoration and conservation to create intact, continuous RFBs upstream into the headwaters should be considered as a watershed-scale strategy to mitigate threats of increased stormwater and flooding.

Buffered riparian zones designed to consider landscape characteristics can support species migration (Graziano, Deguire, & Surasinghe, 2022; Bentrup, 2008) as changes in habitat ranges are threats to wildlife, fish, and plant life. Models can be used to predict how tree species ranges may shift by the year 2100. The average centers of suitable habitat may shift between 60 to 350 mi. under high emissions scenarios and between 30 to 240 mi. under milder climate change scenarios (Iverson et al., 2004a as cited in Buter-Leopold, 2018).

Riparian forest buffers that provide a continuous corridor of intact habitat can increase the resilience of species that have limited capacity to disperse across long distances by helping to maintain genetic diversity in species with small, declining, or isolated populations (Graziano, Deguire, & Surasinghe, 2022). To optimize riparian forest buffers for the resilience of species and assisted migration at the regional-scale, a strategy of stepping stones and coordinators may offer the most opportunities for species dispersal and migration (Bentrup, 2008). That is, if it is not possible to have a continuous corridor of intact forest buffer, small patches of forests can allow for species movement between large patches; however, smaller or more specialized species will generally tolerate smaller distances between patches (Bentrup, 2008). Corridors—including intact buffers and patches connecting them—will be most effective if they are oriented along projected changes in climate gradients (Bentrup, 2008), which in the Mid-Atlantic region will generally shift northward (USDA, 2023).

Design

RFB restoration is complex and multi-faceted. RFB design, including width, species selection, and spacing and layout should be tailored to address the greatest threats facing nearby communities.

Width

In general, wide buffers provide greater benefits to communities than narrow buffers, optimizing climate adaptation and resilience. Wider buffers provide a greater variety of co-benefits and are more likely to sustain those benefits longer (Alliance for the Chesapeake Bay, 2004). Site-specific characteristics can help inform optimal width in buffer designs. For example, areas with steep slopes may need a wider RBF to offset the faster runoff (Alliance for the Chesapeake Bay, 2024; Bentrup, 2008), as will areas with finer textured soil as they have lower infiltration capacity and need more surface area to accept runoff than places with great infiltration capacity (Bentrup, 2008). In places where wide, fixed-width buffers are not possible, variable-width buffers that are wider where runoff concentrates into flow paths as it flows downhill may be effective (Bentrup, 2008). There are several methods available to determine the minimum width of a buffer needed at a specific site, which may include soil surveys, slope distance from pollutant source and stream characteristics (Welsch, 2017).

TABLE 3 RIPARIAN BUFFER ZONES: FUNCTIONS AND RECOMMENDED WIDTHS (ELLEN HAWES AND MARKELLE SMITH, YALE SCHOOL OF FORESTRY, APRIL 2005 AS CITED IN (HORNER, 2014)

Benefits or eco-services provided	Recommended buffer widths
Erosion/sediment control:	30 feet to 98 feet
Water Quality:	
Nutrients	49 feet to 164 feet
Pesticides	49 feet to 328 feet
Biocontaminants (fecal, etc.)	30 feet or more
Aquatic habitat:	
Wildlife	33 feet to 164 feet
Litter/debris	50 feet to 100 feet
Temperature	30 feet to 230 feet
Terrestrial habitat	150 feet to 330 feet

Complete headwaters reforestation is not necessary to achieve optimal flood mitigation—a buffer that is at least 500 meters wide (1640 ft.) has been shown to reduce impacts of increased stormwater and flooding—especially peak flows—to a similar extent as complete reforestation of the watershed (Palmer R. N., Nislow, Ericson, & Backiel, 2019). However, the impact of wider riparian forest buffers locally may have ramifications upstream. As buffer width increases, the peak flow of floods may decrease and flood arrival time may be delayed, but the stage, duration, and number of flooded buildings in the floodplain may increase substantially as compared to buffers with field land uses (Palmer R. N., Nislow, Ericson, & Backiel, 2019). This consideration is another example of the necessity of considering watershed-scale planning in riparian forest buffer restoration strategies.

When considering the benefits that buffers provide as migration corridors for shifting species ranges, broad connectivity zones may be more effective than distinct, narrow corridors (Bentrup, 2008). Wider buffers provide habitat sizeable enough to ensure resilient populations of wildlife, fish and plant life (Bentrup, 2008), and significantly reducing nitrogen in groundwater (Messer et al., 2012 as cited in Washington et al., 2024). While RFBs can mitigate temperatures locally, heated waters can potentially bypass narrower buffers, so wider buffers along with upstream practices should be where increased water temperatures threaten aquatic species (Batiuk R. B.-N., 2023).

While many forest buffer restoration programs require a minimum 30 ft. buffer width, most nitrate reduction in shallow groundwater occurs within 30 to 100 ft. of entering a buffer (Bentrup, 2008). Research indicates that groundwater nitrate may bypass narrow riparian forest buffers and discharge directly into streams unaltered (Palone & Todd, 1997). In short, wider buffers are more effective at reducing pollution (Alliance for the Chesapeake Bay, 2004).

Species selection

The level to which vegetated buffers can mitigate the impacts of increased stormwater and flooding, threats to fish, wildlife and plant life, changes in water supply and other community impacts can also be influenced by the species selected in riparian restoration.

While riparian forest buffers may have lower peak flow which result in longer warning times in advance of storm events and flooding, fielded land cover (i.e. grasses and other herbaceous vegetation) in riparian areas may have shorter flood duration and fewer buildings flooded than compared to forested buffers (Palmer R. N., Nislow, Ericson, & Backiel, 2019). Trees planted in the buffer Zone 1—closest to the edge of the stream—can mitigate flood impacts more effectively than shrubs and bushes because bushes can flatten during high flows (Thomas & Nisbet, 2007). Species selection, therefore, should optimize the co-benefits to mitigate against a variety of threats facing communities.

Riparian areas have disproportionately high species richness and density of wildlife compared to nearby habitats (Odum, 1979 as cited in Graziano et al., 2022). Environmental complexity caused in part by temporal variations (e.g. natural disturbances throughout the year) and spatial variations (e.g. variations in soils and groundwater) have resulted in species that may be more resilient or resistant to climate change (Capon et al., 2013 as cited in Graziano et al., 2022). Faced with greater frequency of extreme environmental conditions, forest communities with greater species diversity exhibit greater resilience (Forrester and Bauhous 2016 as cited in Bulter-Leopold et al., 2018; Isabell et al., 2015 as cited in Butler-Leopold et al., 2018). Species with high genetic diversity are more likely to have individuals that can adapt to environmental changes over time (Reuschoet al., 2005 as cited in Bulter-Leopold et al., 2018), so plants used for restoration projects should be sourced from separate populations to encourage RFB resilience. Species diversity should also consider the reliance of aquatic insects on leaf fall—a mix of species may provide prolonged stable leaf fall and the variety needed to support healthy aquatic insect populations (Welsch, 2017).

While many native RFB species are expected to remain stable or increase (Butler-Leopold P. R., et al., 2018), in the Mid-Atlantic there are northward trends in plant hardiness zones (USDA, 2023). Species that are adapted to particular environments (Butler-Leopold P. R., et al., 2018) and those that cannot adapt quickly enough to cope with a changing climate (PA DCNR, 2021) are not likely to thrive. Further, if climatic conditions change quickly, invasive species that are highly mobile and adaptable may be able to out-compete native species in migration (Bentrup, 2008). Therefore, it is essential to select plants with high climate resilience and/or migration potential in buffer designs.

Species selected for RFB restoration in areas where nitrogen in water supplies is a concern should consider the ability of different species to take up and store nutrients under site-specific conditions (Palone & Todd, 1997). For example, some newly planted bottomland hardwood seedlings like water tupelo grow faster where riparian soils are saturated (Palone & Todd, 1997). Additionally, rooting depth should be considered because riparian forest buffers can only remove nitrate from groundwater where roots are deep enough to intercept groundwater flow (Bentrup, 2008).

Modeling efforts can help us understand and evaluate the potential capability of tree species to cope or persist in a changing climate. The lists in Table 4 are provided as examples of resources available to project species vulnerability and adaptability due to a variety of changing environmental conditions and is a general starting point for communities to implement resilient RFBs. The species provided in these resources were narrowed down for illustrative purposes to a small selection that may be found in riparian forest buffers. The list is not comprehensive, and not all species may be suitable for all restoration projects depending on hardiness zones and local conditions. More information about the methods used can be found through the links provided. A helpful, central location for information about the potential suitable habitat for tree species across the eastern United States can be found at the USDA Forest Service Climate Change Tree Atlas: https://www.fs.usda.gov/nrs/atlas/tree/

TABLE 4: EXAMPLES OF RESOURCES AVAILABLE TO PROJECT SPECIES VULNERABILITY AND ADAPTABILITY

Pennsylvania Climate Effects: Heat and Hardiness Zones (Matthews et al., 2018 as summarized by Northern Institute of Applied Climate Science & Pennsylvania DCNR, 2018)	
Methods: This research builds on the Climate Change Tree Atlas with additional species and compares current with future projections of hardiness zones and heat zones for regions of Pennsylvania. As temperatures increase, it is expected that hardiness and heat zones will shift.	
Geography: All of Pennsylvania, excluding the Erie and Ontario Lake Plain subregion.	High adaptability: Downy serviceberry, Smooth hawthorn, Serviceberry, Smooth sumac, Staghorn sumac, Witchhazel. Medium adaptability: American hazelnut, Gray dogwood, Red osier dogwood, Southern catalpa
Climate Change Projections for Individual Tree Species: Greater Baltimore, MD (Iverson et al., 2019 as summarized by NIACS, 2021)	
Methods: These future climate projections (2070 to 2099) provide information about how individual tree species may respond to a changing climate. Considers suitable habitat, adaptability, capability, and migration potential models.	
Geography: Greater Baltimore, Maryland	Capability to cope or persist with climate change: Poor: Black ash, Pawpaw, Pin oak, Swamp white oak, Quaking aspen Fair: American beech, Bitternut hickory, Black locust, Black walnut, Eastern cottonwood, Sassafras, Red mulberry Good: Boxelder, Northern red oak, Red maple, Sugar maple, Swamp chestnut oak, Sycamore, Yellow Poplar Mixed results: Common persimmon, Black willow New habitat with migration potential: Eastern redbud, River birch, water oak, Water tupelo
Mid-Atlantic Forest Ecosystem Vulnerability Assessment and Synthesis: A Report from the Mid-Atlantic Climate Change Response Framework Project (Butler-Leopold P. R., et al., 2018)	
Methods: Potential impacts on forests were identified by future climate projections into three forest impact models: DISTRIB, LINKAGES, and LANDIS PRO.	
Geography: Mid-Atlantic	Projected declines in growth and suitable habitat: American beech, eastern hemlock, eastern white pine, red spruce, and sugar maple. Projected to persist or increase: black oak, northern red oak, pignut hickory, sweetgum, and white oak.

Spacing and layout

Spacing and layout design characteristics for RFB restoration projects include stem density, vertical and horizontal structures and proximity of each species and vegetation type to the stream bank.



FIGURE 11 AN RFB RESTORATION PROJECT ON A FARM IN CARROLL COUNTY, MD. CREDIT: ALICIA PIMENTAL/CHESAPEAKE BAY PROGRAM

Riparian forest buffers are often designed with a structure of three zones, each providing unique benefits. Zone 1, the closest to the stream, consists primarily of trees that regulate water temperature by providing shade, reduce erosion by enhancing bank stabilization, and enhance habitat complexity through root systems and woody debris supplied to the waterway (Graziano, Deguire, & Surasinghe, 2022). Zone 2, the middle zone, often consists of a mix of trees and shrubs that assimilate nutrients, reduce sedimentation to streams by retaining fine sediments, and enhance groundwater recharge, benefitting both water supplies and flooding mitigation (Graziano, Deguire, & Surasinghe, 2022). Zone 3, the outermost zone, may consist primarily of herbaceous vegetation like grasses and forbs, which act like a physical barrier to stormwater runoff, ultimately reducing the volume and velocity of runoff flowing toward the stream during storm events and reducing erosion and retaining silt and sediment (Graziano, Deguire, & Surasinghe, 2022).

Choices about stem number and vegetative roughness can optimize the capacity of near stream areas to impede flood flows (Thomas & Nisbet, 2007). For example, factors such as the spacing and layout of trees, presence of lower branches, level of undergrowth and amount of dead wood on the woodland floor can all be considered when designing the RFB forest stand composition to ensure it addresses local flood concerns (Thomas & Nisbet, 2007).

At the project scale, the thermal benefits of shading provided by zone 1 of RFBs can be optimized by considering channel orientation (Dugdale, Malcolm, Kantola, & Hannah, 2018), i.e., maximizing shading by planting trees more densely on the immediate south-facing banks of the stream.

In places where groundwater is enriched with nitrogen and discharging directly into the stream, planting deeply rooted vegetation near the stream channel may have some effect on nitrogen

removal (Palone & Todd, 1997). In karst landscapes, RFBs planted around sinkholes and sinking streams can minimize nitrate pollution entering directly into groundwater (Bentrup, 2008).

Additional considerations

To optimize the benefits and support the resilience of RFBs, there are many other considerations to include in decision-making that will help ensure RFBs are effectively installed and have long-lasting benefits to communities' climate adaptation and resilience. The additional considerations below are not exhaustive but help reinforce the idea that implementing RFB policies and programs should have a diversity of stakeholders at the table in addition to those providing technical guidance on siting and design.

- Tradeoffs and co-benefits: There are tradeoffs to consider when buffer siting and design is aimed at achieving a particular set of benefits. For example, species that are best at denitrification may not be ideal for bank stabilization. Therefore, communities may consider optimizing the co-benefits of RFB implementation. Some examples may include partitioning the RFBs into areas suited to different, competing functions; planting priority species at higher densities; and creating buffers with a diversity of species and structures to achieve multiple benefits (Rubin J. , McGranaghan, Kolba, & Görres, 2024). Multifunctional buffers, or those designed for both production (like growing fruits, nuts, and other products for harvest) as well as conservation goals, can increase the potential for larger riparian buffers by making them more appealing in relation to competing land uses.

- Restoration in conjunction with long-term protection: With a goal of buffering 70% of all streams and shorelines with forests outlined in the Chesapeake Bay Watershed Agreement, conserving existing forests is a key strategy to success. This goal is set in part to ensure ecosystem services are delivered to communities across the Chesapeake, therefore, existing riparian forest buffers should be prioritized for permanent protection as mature forests are the ultimate goal of RFB restoration. For example, newly planted buffers are not as effective as established buffers in mitigating the threats of increased stormwater and flooding: the largest reductions in peak flow occur where 22-50% of sub-catchments in the channel network are restored after 25 years of forest growth (Dixon, 2016). When considering the resilience of RFBs as they face climactic changes over the next century, many tree species are expected to lose the potential to regenerate, but absent other mortality factors, mature trees could continue to grow for much longer (Butler-Leopold P. R., et al., 2018). These mature individuals in existing forests may retain ecosystem services until buffer areas are populated with new species more suited to the new environmental conditions.

- Complementarity with other best management practices: In communities where impacts from increased stormwater and flooding are a concern, a technique to reduce channel velocity may be to incorporate in-stream structures in stream restoration projects (i.e. woody debris dams) (Broadmeadow & Nisbet, 2010). Given the complexities of riparian forests impacts on flood duration and flooded buildings in floodplains (all of which increase under forested scenarios as opposed to field land use in riparian areas), integrated flood management plans likely need to utilize structural best management practices for optimal protection (Palmer R. N., Nislow, Ericson, & Backiel, 2019). Features that increase water tables such as extended detention basins and shallow marshes have been shown to mitigate increased nitrogen in surface and groundwater, and could be considered in watershed-scale planning alongside riparian reforestation strategies (Washington, Groffman, Duncan, Band, & Miller, 2024). Further, constructed wetlands may be necessary in places where drain tile pipes or ditches cause groundwater flow to bypass buffers, preventing the denitrification from RFBs (Bentrup, 2008). While riparian forest buffers are effective at preventing some amount of nutrients from runoff from entering streams, RFBs should be used in conjunction with upslope best management practices to address the issue at its source (Welsch, 2017).

- Maintenance: Maintaining the health of a newly planted riparian forest buffer is essential to ensuring long-term survivorship, ongoing delivery of ecosystem services, and landowner buy-in. During establishment, mowing may be necessary to suppress fast-growing invasive species and other pests from outcompeting or damaging plantings. Tree mortality is expected after planting, and trees should be replaced during the first few years of buffer establishment. Examples of longer-term maintenance may include periodic minor ground shaping to manage concentrated flows, which may result in erosion as well as runoff bypassing the buffer; and for long-term nitrogen removal, trees may be harvested periodically to maintain system efficiency (Welsch, 2017).

- Landowner priorities: Conflicting land uses will remain a challenge to optimum siting, infrastructure such as sewer, roads, greenway trails and the human desire for waterfront property pose threats to restoring RFBs. In agricultural settings, farmers can consider the tradeoffs of losing cropland to riparian forest buffers versus the benefits of preventing soil loss (Wu, Khalid, Mitchell, & Ha, 2024). Buffers can be designed in conjunction with landowner goals to ensure buy-in and long-term stewardship. For example, to balance agricultural production and conservation goals, landowners and restoration professionals can consider integrating fruit, nut, timber, and/or bioenergy crops into buffer designs to create multi-functional buffers (Stanek, Lovell, & Reisner, 2019). Conservation and restoration professionals should also develop stronger engagement with private landowners to promote RFBs for their stream temperature moderating effects (Batiuk R. B.-N., 2023) which could be especially effective in areas where coldwater fishes like Brook Trout have cultural significance.



FIGURE 12 A LANDOWNER DESCRIBES HIS PRIORITIES TO RESTORATION PARTNERS FOR A RIPARIAN FOREST BUFFER PROJECT. CREDIT: CHESAPEAKE CONSERVANCY.

Programs and case studies

While communities throughout the Chesapeake Bay watershed have largely focused on RFBs for water quality, there are examples of policies and programs aimed at RFBs to enhance resilience and adaptation to climate change. Implementation is largely determined by the threats and makeup of the community and may employ various strategies, including:

- Valuing ecosystem services
- Community-based resilience
- Data-driven decision making

Valuing ecosystem services

Assigning economic values to the benefits RFBs provide.

Ecosystems provide a variety of direct and indirect benefits to humans, including provisioning services (material or energy outputs); regulating services (moderation or control of ecosystem processes); supporting services (maintain fundamental ecosystem processes); and cultural services (non-material benefits to society). The services RFBs provide that help communities mitigate and adapt to a changing climate include regulation of local climate, flood and erosion control, habitat for plants and wildlife, freshwater for water supplies, and opportunities for recreation. Programs that value ecosystem services may provide financial incentives to landowners who implement RFBs. Policies may consider the economic value provided by RFBs to communities in comprehensive plans, restoration programs, and budgeting.

Ecosystem services case study

- Maryland 5 Million Trees Initiative, MD: A program designed to plant native trees in riparian areas, focusing on underserved communities

Community-based resilience

Voluntary RFB restoration programs driven by local residents and organizations.

Increasingly, residents of the Chesapeake Bay watershed are recognizing the impacts of climate change in their local communities. Community-based efforts are often driven by local nonprofits or volunteer-based organizations like advocacy groups and watershed associations who incorporate RFBs into the larger context of community improvement efforts. Resident input, voluntary participation and flexibility are keys to success.

Community-based resilience case studies

- Resilience Forward, Resilience Authority of Charles Co., MD: This initiative addresses the threats of climate change by establishing native tree canopies in urban heat islands and developing a conservation workforce, the Resilience Authority Youth Corps (RAYC). This work benefits both human and wildlife communities by creating habitat, providing shade, and absorbing stormwater.
- Middle Branch Resiliency Initiative, MD: This coastal resilience initiative aims to build a network of green space—including 50+ acres of habitat along 11 miles of the Middle Branch of the Patapsco River—to provide more access and ecosystem benefits to the local community.
- Climate Crew, Greater Baltimore Wilderness Coalition, MD: A program to focus on restoration work in under-resourced communities while offering workforce development to under-served communities. This work aims to mitigate the impacts of climate change including seal level rise, flooding, stronger coastal storms, warmer temperatures and drought while selecting species for tree plantings with assisted migration in mind.
- CommuniTree Program, Cacapon Institute, WV: A partnership between the Cacapon Institute and the Town of Romney, WV where partners work with volunteers to install trees along impervious surfaces such as sidewalks and parking lots to manage and cool stormwater runoff along a tributary of the Potomac River.

Data-driven decision-making

RFB strategies guided by research, models and GIS-based prioritization.

There are limited resources available to implement RFB programs in terms of both funding and capacity. Data can guide decision-makers toward implementing RFB programs that can make the most out of limited resources, optimizing the benefits of RFBs. Field-based research studies, high-resolution GIS data, and climate change models are among the types of data that, when combined, can target outreach and implementation where conservation and restoration of RFBs can most effectively address the challenges facing communities.

Data-driven decision-making case studies

- PA 30 by 30 Stream Delisting, PA: A strategy to improve water quality in small communities using local partnerships to implement practices. High-resolution datasets from this strategy

are used to prioritize riparian forest buffer restoration and create continuous RFB habitat to stabilize stream banks, provide habitat, and mitigate erosion and nutrient inputs.

- Upper Susquehanna Coalition's Water Quality Program, NY and PA: A coalition of 22 soil and water conservation districts across NY and PA working to implement riparian and stream restoration work through collaborative fundraising to improve water quality. The USC developed a series of datasets to identify climate change resiliency-oriented best management practices in the watershed, focused on wetland and riparian restoration opportunities.

Summary: Case studies

These case studies provide examples of projects that demonstrate RFB benefits to mitigate threats and where project design or siting criteria maximize community and RFB resilience. Case studies represent the array of adaptation benefits and resiliency strategies described in the synthesis report. Table 5 demonstrates the relationship between the case studies, the policy and program strategies employed, and the threats addressed and ways each program maximized RFB benefits.

TABLE 5 CASE STUDIES BY POLICY AND PROGRAM STRATEGIES; CLIMATE CHANGE TOPICS COVERED

	Threats addressed			Maximizing benefits		
Policy and program strategies	Increased storm events and flooding	Threats to fish, wildlife and plant life	Changes in water supplies	Siting	Design	Resilience of RFBs to climate change
Valuing ecosystem services		MD 5M Trees				MD 5M Trees
Community-based resilience	CommuniTree MBRI RAYC Climate Crew	CommuniTree MBRI RAYC Climate Crew	MBRI	CommuniTree MBRI	Climate Crew	Climate Crew
Data-driven decision-making and progress tracking	USC PA 30 x 30	USC PA 30 x 30		USC PA 30 x 30	PA 30 x 30	PA 30 x 30

Conclusion

The impacts of climate change are already being felt throughout the Chesapeake Bay watershed. Data shows that air and water temperatures are increasing. Precipitation is expected to increase overall, with more in the winter and spring and likely less in the summer and fall. These changes, among others, are likely to drive increases in stormwater and flooding, threaten fish, wildlife, and plant life, and result in changes in water supplies. RFBs can mitigate stormwater and flooding impacts by reducing flood peaks, giving more time to issue flood warnings, and mitigating increases in bank erosion. RFBs help ecosystems moderate stream temperatures, accommodate shifting species ranges, and provide resilience against invasive species and pests. RFBs lessen impacts to water supplies, riparian forest buffers can mitigate nitrogen inputs and encourage denitrification in surface and groundwater, while supporting the availability of water supplies. Implementing riparian forest buffers enhances both ecological health and human communities.

When appropriately sited and designed, RFBs can optimize climate adaptation and resilience to impacts. However, RFBs are under threat from a changing climate as well. Wider buffers tend to provide greater benefits, species selection should consider an expected northward shift in habitat ranges, and layout and design can optimize the mitigation of threats.

Seven case studies demonstrate that there are multiple strategies that communities can use to implement RFB policies and programs. All programs and designs should consider community context. They should incorporate projected changes to the landscape and climate to ensure RFB resilience. Riparian areas are not only corridors of connected habitat along waterways but can be connections between communities as they adapt to threats of increased storm events and flooding, threats to fish, wildlife and plant life, and changes to water supply.

Communities across the Chesapeake Bay watershed play a pivotal role in determining flooding impacts, ecosystem health, and the availability of surface and groundwater both locally and downstream. Riparian buffers act as interconnected corridors along waterways, meaning their ecological and climate benefits extend beyond jurisdictional boundaries. When implemented and maintained strategically across the watershed, buffers contribute to the collective resilience of the entire Bay ecosystem.

The report emphasizes that approaches that coordinate upstream and downstream communities are key to optimizing the benefits of riparian forest buffers. Case studies demonstrate that communities must recognize their shared dependency on resilient, intact, continuous riparian forest buffers and work together through regional partnerships and watershed-scale planning. This includes addressing barriers such as funding, landowner participation, and capacity constraints

equitably across communities. Policies and programs should support landowners with technical assistance and incentives to restore and protect riparian buffers, while fostering local leadership and co-stewardship across municipal and state lines. Riparian forest buffers also offer opportunities for climate-smart economic development through green jobs, nature-based tourism, and sustainable agriculture. When integrated into broader climate action strategies, RFBs build long-term climate adaptation and resilience, making them a cornerstone of nature-based solutions in the region.

Ultimately, protecting and expanding riparian forest buffers is not only an environmental imperative but a social and economic one. By acting as natural connectors across the landscape, buffers symbolize the interdependence of upstream and downstream communities and highlight the need for unified, place-based, and climate-forward action across the Chesapeake Bay watershed.



FIGURE 13 RIPARIAN FOREST BUFFER IN YORK CO., PENNSYLVANIA WITH ALLIANCE FOR THE CHESAPEAKE BAY. CREDIT: WILL PARSON/CHESAPEAKE BAY PROGRAM.

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Appendix: Annotated bibliography

Alliance for the Chesapeake Bay. (2024). *Riparian Forest Buffers: Linking Land and Water.* Chesapeake Bay Program.

The report discusses conservation and restoration of streamside forests in the Chesapeake Bay watershed. Functions and benefits include filtering pollution, sustaining aquatic habitat, stabilize floodplains, transforming and storing nutrients, providing shade, and providing wildlife habitat. To maximize the benefits, communities should consider the location and width of the buffer. The Chesapeake Bay Riparian Forest Initiative aims to increase conservation and maintenance and accelerate progress toward Bay-wide riparian forest buffer goals.

Batiuk, R. B.-N. (2023). *Rising Watershed and Bay Water Temperatures--Ecological Implications and Management Responses – A STAC Workshop.* Edgewater, MD.: STAC Publication Number 23-001.

This paper summarizes the recommendations of members of a Science and Technical Advisory Committee, providing guidance to the Chesapeake Bay Program following a workshop, review, forum, conference, and other activities. As atmospheric temperatures increase, water temperatures are expected to continue rising as a result of climate change. Increased water temperatures are also impacted by land use, but can be mitigated by installing "cooling" best management practices such as riparian forest buffers, urban tree canopy, and stormwater infiltration. Research is already showing northward shifts in species ranges as well as negative impacts to aquatic habitats. More monitoring and modeling needs to be done to continue to mitigate impacts of climate change. Key design considerations are focused on a “stepping stone” approach to support species migration.

Batiuk, R., Brownson, K., Dennison, W., Ehrhart, M., Hanson, J., Hamner, R., . . . Vogt, B. (2023). Rising Watershedand Bay Water Temperatures: Ecological Implications and Management Responses – A STAC Workshop. 505.

A report following a workshop of the Chesapeake Bay Program's Science and Technical Advisory Committee. Findings include that the drivers, effects and likely management implications of water temperature increases are quite different between the Bay and the watershed.

Bentrup, G., 2008. *Conservation buffers: design guidelines for buffers, corridors, and greenways.,* Asheville, NC: s.n.

This technical report provides general guidelines for the planning and design of riparian forest buffers based on a review of over 1,400 research publications. Co-benefits are discussed to optimize riparian forest buffers to protect soil, improve air and water quality, enhance fish and wildlife habitat, produce economic products, provide recreation opportunities, or beautify the landscape. Riparian forest buffers may impact projected climate change by reducing greenhouse gases, allowing species to migrate, protecting sensitive areas from floods and storm surfaces, and providing microclimate refugia.

Bhatt, G. et al., 2023. Water quality impacts of climate change, land use, and population growth in the Chesapeake Bay watershed. Journal of the American Water Resources Association, Volume 59, p. 1313–1341..

Due to the combined pressures of climate change and growth in population, agricultural intensity, and economic activity, the tidal Chesapeake Bay is expected to experience significant changes. Increases in air, water temperature, and evapotranspiration rates by the year 2025 and will likely be the main driver for expected increases in streamflow, nitrogen, phosphorus, and sediment to the tidal Bay.

Bowler, D. E., Mant, R., Orr, H., Hannah, D. M., & Pullin, A. S. (2012). What are the effects of wooded riparian zones on stream temperature? *Environmental Evidence, 1*(3).

There is a growing body of evidence to suggest that stream water temperature is increasing, and this study suggests that riparian wooded zones lower spring and summer stream temperatures, particularly in terms of maximum temperatures. Because temperature is known to affect fish, amphibian and invertebrate life history, the reported effect sizes are likely to have a biological significance for the stream biotic community. Consequently investment in creation of wooded riparian zones might provide benefits to mitigate the ecological effects of climate change on water temperature.

Braithwaite, N. T., & Mallik, A. U. (2011). Edge effects of wildfire and riparian buffers along boreal forest streams. *Journal of Applied Ecology, 49*(1), 192-201.

The study evaluated the impacts of different edge structures on disturbances in boreal forests. The results indicate that the ecological structure at buffer and fire edges in boreal forests creates different environmental filters supporting different plant assemblages. Recommendations include replacing sharp edges of a riparian clear-cut buffer with feathered edges to help conserve biodiversity.

Broadmeadow, S., & Nisbet, T. (2010). Opportunity mapping for woodland to reduce flooding in the Yorkshire and the Humber region, Forest Research Monograph, 1, Forest Research, Surrey, 64pp. *Forest Research Monograph*, 64.

This study considered different restoration strategies for riparian forest buffers to mitigate the impacts of flooding. GIS was used to identify areas that are vulnerable to flooding where trees could be planted. The resulting prioritization highlighted areas for planting based on the relative vulnerability of soil types within the catchment to generate rapid surface runoff, degrade structurally and/or deliver sediment to watercourses. Established riparian woodland can alleviate flooding downstream through the action of woody debris dams, which impede water flow and promote out of bank flows. This has an overall impact of reducing and delaying the flood peak. Riparian woodland can help to reduce sediment delivery from the adjacent land, controlling siltation and increasing the flood storage capacity of river channels. Tree rooting acts to stabilize and strengthen riverbanks, reducing bank erosion and sedimentation. Another benefit of woodland is the ability to protect soil from disturbance and improve soil structure due to greater inputs of organic matter and the action of tree roots. These conditions enhance soil infiltration and water storage capacity thereby reducing surface run-off and delaying the passage of rainwater to streams and rivers. The benefit for flood mitigation is likely to be greatest where woodland replaces more damaging land uses on sensitive soils that are likely to promote rapid run-off due to soil sealing and compaction.

Brooks, K., Norman, C., & Kreye, M. (2024, January 8). *Penn State Extension*. From Climate Change Effects on Pennsylvania's Forests: https://extension.psu.edu/climate-change-effects-on-pennsylvanias-forests

This article details climate change and its impacts across the Mid-Atlantic region, specifically to higher air temperatures (increase on average by 5.27 to 9.11°F by the end of the century) and precipitation (total precipitation projected to increase but distributed unevenly with more intense precipitation events). It is predicted that there will be a change in species distribution, a loss of diversity, increased occurrence of insect outbreaks, and new invasive species.

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

This study evaluates the vulnerability of forest ecosystems across the Mid-Atlantic region (Pennsylvania, New Jersey, Delaware, eastern Maryland, and southern New York) to different climate scenarios. Average temperatures and total precipitation has already increased, and many mesic tree species are projected to decline, while species that tolerate hotter, drier species are projected to persist or increase. Montane spruce-fir and lowland conifer forest communities are the most vulnerable ecosystems.

Chesapeake Bay Foundation. (2022, July 22). *Hurricanes, Heat Waves, and Unpaving Paradise*. From Save the Bay News: https://www.cbf.org/blogs/save-the-bay/2022/07/save-the-bay-news-hurricanes-heat-waves-and-unpaving-paradise.html#:~:text=Fifty%20years%20ago%20last%20month,say%2C%20a%20forever%20changed%20Bay.

Climate change is shifting what is "normal" across the Chesapeake Bay watershed, including more regular or intense heat waves. Devastating heat waves, major storms (like Hurricane Agnes in 1972 which resulted in 122 fatalities) and severe flooding should be expected, while water temperatures continue to rise. However, communities are working to mitigate these impacts, such as in the two case studies of tree plantings in Baltimore City, MD and un-paving parking lots in Richmond, VA.

Chesapeake Progress. (2024). *Climate Monitoring and Assessment*. From Chesapeake Progress: https://www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment#:~:text=In%202021%2C%20all%2033%20of,time%20period%20from%201901%2D2000.

This page summarizes monitoring to assess trends and likely impacts of climate change across the Chesapeake Bay watershed. In 2021, all 33 climate divisions in the watershed have experienced statistically significant increases in average air temperature compared to the time period from 1901-2000. Annual precipitation in some parts of the watershed have increased, with the greatest increases in New York and parts of Pennsylvania.

Chesapeake Progress. (2024). *Forest Buffers*. From https://www.chesapeakeprogress.com/abundant-life/forest-buffers

This page tracks the goals of the Chesapeake Bay Program to restore 900 miles of riparian forest buffers per year and conserve existing buffers until at least 70 percent of riparian areas in the watershed are forested. Overall, the buffer outcomes are off course, often achieving less than 10% of the annual goals with a trend of a net loss.

Dixon, S. J. (2016). The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms, 41*(7), 997-1008.

This study used models to assess how different spatial configurations of restoration activities affect flood hydrology. Restoring riparian forests in the middle and upper parts of a catchment can reduce peak flows during a flood by desynchronizing the timing of flood peaks. As riparian forests mature, hydraulic resistance in the channel and floodplain grow as the forest contributes more deadwood to the channel. The largest reductions in peak flow occur for scenarios where 22-50% of sub-catchments in the channel network are restored after 25 years of forest growth (mean reduction of 10% peak discharge). In summary, large-scale restoration is needed to see an impact on peak flows.

Dugdale, S., Malcolm, I. A., Kantola, K., & Hannah, D. M. (2018). Stream temperature under contrasting riparian forest cover: Understanding thermal dynamics and heat exchange

processes. *Understanding thermal dynamics and heat exchange processes, 610-611*, 1375-1389.

The article addresses concerns over impacts of climate change on stream temperatures as stream temperatures is one of the principal river habitat variables impacting biological process Climate change is likely to increase summer temperatures in many river environments, raising concerns that this will reduce their thermal suitability for a range of freshwater fish species. The research contrasts stream temperature and energy fluxes under three riparian vegetation types: open grassland, semi-natural deciduous woodland, and commercial conifer plantation. The findings can influence decisions on riparian forest buffer design, but overall, temperature is influenced by a variety of environmental variables including patterns of upslope land use and topography. In general, grasses are not effective at blocking incoming solar radiation, resulting in much higher stream surface temperatures than forested buffers and the ability to moderate summer stream temperatures is similar among deciduous and coniferous forests.

EASPE, Inc. (2002). *Use and Benefits of the National Weather Service.* National Hydrologic Warning Council.

This paper outlines and quantifies the economic impacts to communities from weather and climate events, in particular to agriculture, forestry, fishing, energy, transportation, and the construction industry; public utilities; finance and insurance; retail trade; hotels and recreation; and public/private property losses. Hydraulic forecasts and warnings are effective in reducing flood damages, and advanced notice to communities in the event of a flood can save lives and reduce economic losses. Further, long-range hydraulic forecasts can result in millions of dollars of annual benefits including flood loss reduction, in addition to hydropower, irrigation, navigation, and water supply.

Eisenbies, M. H., Aust, W. M., Burger, J., & Adams, M. (2007). Forest operations, extreme flooding events, and considerations for. *Forest Ecology and Management, 242*, 77-98.

This study looks at how riparian forest buffers can influence the impact of stormwater and flooding. In general, soils in forests have greater infiltration capacity. This is due in part to evapotranspiration: a relatively high percentage of rainfall is lost to evapotranspiration and therefore doesn't contribute to stormflow. There are upstream considerations to

implementing riparian forest buffers downstream: large woody debris from riparian areas can either increase flood hazards by constraining the channel or can help slow down stream flow locally, therefore, the position of buffers must be considered in relation to the condition of upstream channels.

Graziano, M. P., Deguire, A. K. & Surasinghe, T. D., 2022. Riparian Buffers as a Critical Landscape Feature: Insights for Riverscape Conservation and Policy Renovations. *Diversity,* 14(172).

Riparian zones are critical for functional integrity of riverscapes and conservation of river-scape biodiversity. Riparian zones provide critical habitat and climatic refugia for wildlife and may serve as migration corridors, providing a diversity of in-stream habitats including deep, cool pools that help mitigate increased stream temperatures. Riparian vegetation intercepts surface-runoff enhancing groundwater recharge and mitigating flooding. The riparian buffer design should harmonize with the riverscape concept considering both local and watershed-scale factors, including ensuring upstream forested headwaters are preserved to mitigate impacts of upstream flooding when restoration downstream slows flows. The researchers suggest the adoption of variable width buffers to optimize riparian forest buffer co benefits.

Hickman, J. E. & Lerdau, M. T., 2013. Biogeochemical impacts of the northward expansion of kudzu under climate change: the importance of ecological context. Ecosphere, 4(10), pp. 1-15.

Kudzu (*Pueraria montana*) has large impacts on nitrogen (N) cycling and trace N gas emissions in the southeastern United States. To understand how its projected northward migration under climate change will impact ecosystems in the northeastern United States, the researchers examine the impacts of kudzu in the Mid-Atlantic region by pairing plots invaded by kudzu with adjacent uninvaded plots.

Iverson, L. R., Prasad, A. M., Peters, M. P., & Matthews, S. N. (2019). Facilitating Adaptive Forest Management under Climate Change: A Spatially Specific Synthesis of 125 Species for Habitat Changes and Assisted Migration over the Eastern United States. *Forests, 10*(11), 989. doi:https://doi.org/10.3390/f10110989

The synthesis provides a detail dataset to estimate potential species trends out 100 years under potential future changes to climate and includes habitat quality, land cover, and dispersal potential for nearly all the tree species of the eastern United States.

Johnson, L. R., Johnson, M. L., Aronson, M. F., Campbell, L. K., Carr, M. E., Clarke, M., . . . Sonti, N. F. (2020). Conceptualizing social-ecological drivers of change in urban forest patches. *Urban Ecosystem, 24*(4), 633-648.

The research introduces a conceptual model of the urban forest patch as a complex social-ecological system, helping to provide insights into the role of social-ecological drivers in shaping forest health, biodiversity, and benefits forest patches

Johnson, L. R., Trammell, T. L., Bishop, T. J., Barth, J., Drzyzga, S., & Jantz, C. (2020). Squeezed from All Sides: Urbanization, Invasive Species, and Climate Change Threaten Riparian Forest Buffers. *Sustainability, 12*(4). doi:https://doi.org/10.3390/su12041448

Across 100 sites in the Chesapeake Bay and Delaware Bay watershed, there were non-native invasive plants in 94% of forest plots, trees were predominantly native, but over half of shrub stems were invasive species and more than 80% of plots contained invasive woody vines.

Knouft, J. H., & Ficklin, D. L. (2017). The Potential Impacts of Climate Change on Biodiversity in Flowing Freshwater Systems. *Annual Review of Ecology, Evolution, and Systematics, 48*, 111-33.

Increases in air temperature and changing precipitation patterns are altering water temperatures and flow regimes in freshwater systems. Stream water temperatures are expected to warm and species are responding to these changes at all levels of biological organization. Freshwater species and ecosystems also exhibit spatially varying sensitivity to changes in environmental conditions. As a result, accurate estimates of the impacts of climate change must reflect the spatially varying sensitivity of hydrologic systems to changes in climate, as well as the intraspecific and interspecific variations in ecological sensitivity to changes in freshwater environmental conditions.

Knouft, J. H., Botero-Acosta, A., Wu, C.-L., Charry, B., Chu, M. L., Dell, A. I., . . . Herrington, S. J. (2021). Forested Riparian Buffers as Climate Adaptation Tools for Management of Riverine Flow and Thermal Regimes: A Case Study in the Meramec River Basin. *Sustainability, 13*, 1877.

Riparian buffers offer benefits to mitigating increases in water temperature due to shading effects and the addition of riparian buffers is also projected to reduce the impacts of climate change on Smallmouth Bass (*Micropterus dolomieu*) by decreasing the number of days water temperatures exceed the thermal tolerance of this species.

Konrad, C. P. (2003). *Effects of Urban Development on Floods.* From U.S. GEOLOGICAL SURVEY: https://pubs.usgs.gov/fs/fs07603/

Flood peaks are largely influenced by the volume and velocity runoff delivered to waterways during and following storm events. Land use changes associated with urban development increase the peak discharge, volume, and frequency of floods increase in nearby streams. Removing vegetation and soil, grading the land surface, and constructing drainage networks increase runoff to streams from rainfall and snowmelt. Streamflow-gaging stations provide a continuous record of streamflow that can aid flood managers with information to guide flood control operations and emergency actions.

Ladin, Z. S., Eggen, D. A., Trammell, T. L., & D'Amico, V. (2023). Human-mediated dispersal drives the spread of the spotted lanternfly (Lycorma delicatula). *Scientific Reports, 13*. doi:https://doi.org/10.1038/s41598-022-25989-3

The results suggest that human-mediated dispersal (e.g., cars, trucks, and trains) is driving the observed spread of the spotted lanternfly throughout the eastern USA. Factors related to species life history, demography, pathogen susceptibility, enemy release, and climate and habitat suitability all can have important implications for developing and implementing successful management, control, and potentially, eradication strategies.

Langbein, W. B., & Iseri, K. T. (1960). Manual of Hydrology: Part 1. General Surface-Water Techniques. In *Methods and practices of the Geological Survey* (Vols. Geological Survey Water-Supply Paper 1541-a). Washington, DC: United States Department of the Interior.

This guide introduces land managers to concepts of hydrologic techniques to develop and manage water resources including flood damage, irrigation, and reservoir storage. Concepts of data management are presented including how to analyze basic river data and apply them to hydraulic engineering problems. Hydraulic terms used today are defined for a broad audience.

Mallakpour, I., & Villarini, G. (2015). The changing nature of flooding across the central United States. *Nature Climate Change*(5), 250–254.

This article summarizes the societal and economic toll of flooding on communities in the central United States and considers the potential for climate change to increase the magnitude of flood peaks and frequency of flooding.

Maryland Department of the Environment, 2021. Climate Change Adaptation for Maryland Water Utilities, s.l.: s.n.

This brochure was produced by the Maryland Department of Environment's Water Supply Program to assist water utilities to better plan for impacts from climate change. Many of the recommended measures are "no-regrets" options – measures that strengthen the system's resilience and provide benefits under both current conditions and potential climate change conditions.

Marvel, K., Su, W., Delago, R., Aarons, S., Garcia, M. E., Hausfather, Z., . . . Vose, R. S. (2023). Ch. 2. Climate trends. In A. C. Crimmins (Ed.), *Fifth National Climate Assessment.* Washington, DC, USA: U.S. Global Change Research Program. doi:https://doi.org/10.7930/NCA5.2023.CH2

The key messages include that it is unequivocal that human activities have increased atmospheric levels of carbon dioxide and other greenhouse gases and that that global average temperature has risen in response; extreme weather events are becoming more frequent and severe; and that the impacts of climate change increase with warming but rapidly reducing emissions of greenhouse gases would very likely limit future warming.

Modi, P. A., Fuka, D. R. & Easton, Z. M., 2021. Impacts of climate change on terrestrial hydrological components and crop water use in the Chesapeake Bay watershed. Journal of Hydrology: Regional Studies, Volume 35.

This study assessed the impacts of climate change on terrestrial hydrological components and Crop Water Use (CWU) over the Chesapeake Bay watershed using a combination of Global Climate Models (GCMs) and a land surface model. The findings indicate a significant annual increase in precipitation (10 %) and temperature (+4.5 K) for the RCP 8.5 scenario towards the end of the 21st century. The results indicate that even in a warmer regime, crop water use decreased due to rising CO2 concentrations due to climate change.

Northern Institute of Applied Climate Science & Pennsylvania DCNR. (2018). *Pennsylvania Climate Effects: Heat and Hardiness Zones.* From https://forestadaptation.org/sites/default/files/PA_Projected%20Heat%20and%20Hardiness%20Zones.pdf

The fact sheet builds on the Climate Change Tree Atlas by adding additional Pennsylvania species to the analysis. Climate change effects can be assessed by examining future projections of hardiness zones and heat zones for regions of Pennsylvania. The resulting hardiness zone maps include species vulnerability and adaptability of 14 species found in Pennsylvania.

NIACS. (2021). *Climate Change Projections for Individual Tree Species, Greater Baltimore, Maryland.* Northern Institute of Applied Climate Science.

A list of tree species developed by the Northern Institute of Applied Climate Science to aid Greater Baltimore community forest practitioners in selecting trees to reduce climate change vulnerability. The list summarizes the results of the Climate Change Tree Atlas, developed by the Landscape Change Research Group and lists tree species by "Climate Change Capability" in five categories: 1) poor capability, 2) fair capability, 3) good capability, 4) mixed results, and 5) new habitat with migration potential.

NOAA. (2024). *Chesapeake Bay: Climate Change*. From National Oceanic and Atmospheric Administration: Fisheries: https://www.fisheries.noaa.gov/topic/chesapeake-bay/climate-change

This article summarizes the impacts of climate change in the Chesapeake Bay watershed, including sea level rise and increases in air temperature already being documented over the past several decades. Air temperatures have increased from 0.4 to 2.5 degrees Fahrenheit, average water temperature in the Chesapeake Bay has increased by 1.8 degrees Fahrenheit, and the Chesapeake Bay can expect an additional 1.3 to 5.2 feet in sea level rise over the next century.

PA DCNR. (2021, May 01). *Good Natured*. From Pennsylvania Department of Conservation and Natural Resources: https://www.dcnr.pa.gov/GoodNatured/pages/Article.aspx?post=83#:~:text=Some%20tree%20species%20won't,to%20adapt%20before%20dying%20out.

This article published by the Pennsylvania Department of Conservation and Natural Resources (PA DCNR) indicates that some tree species will not thrive in Pennsylvania, as the climate continues to change faster than they can adapt. PA DCNR lists species that are especially at risk, species that are climate resilient and tolerate or prefer wetter soil as well as species that are suitable for a warming climate and prefer well-drained sites. Further, the article suggests forest managers should consider planting trees with fungal and insect resistance and climate change is expanding the habitat of southern pests northward.

Paerl, H. W., Otten, T. G., & Kudela, R. (2018). Mitigating the Expansion of Harmful Algal Blooms Across the Freshwater-to-Marine Continuum. *Environ. Sci. Technol., 52*. doi:10.1021/acs.est.7b05950

This article highlights where paired physical, chemical, or biological controls may improve beneficial uses in the short term, and offers management strategies that should be enacted across watershed scales to combat the global expansion of harmful algal blooms.

Palmer, R. N., Nislow, K. H., Ericson, A., & Backiel, B. (2019). *Reconnecting Floodplains and Restoring Green Space as a Management Strategy to Minimize Risk and Increase Resilience in the Context of Climate and Landscape Change.* University of Massachusetts.

The researchers developed hydraulic models to evaluate how the ratio of forested land to field land within a floodplain impacts flooding. Study findings suggest that as floodplain restoration efforts increase, flood peaks decrease downstream and habitat suitability improves; however, the number of impacted people residing directly in the upstream floodplain can increase. Increasing forested land cover decreases the peak flow but increases the duration of the storm and the number of flooded buildings. By delaying the arrival time of the storm, increasing forest cover could provide a longer time to issue flood warnings. Land changes as small as a 500m forest buffer may reduce peak flows to a similar extent as complete reforestation. Considering upslope land uses and the position of human development within the catchment area is key: preserving the existing tributaries and restoring only the mainstream may optimize human and economic impact.

Perry, L. G., Reynolds, L. V., Beechie, T. J., Collins, M. J., Shafroth, & B., P. (2015). Incorporating climate change projections into riparian restoration planning and design. *Ecohydrology, 8*(5), 863-879.

When considering riparian forest restoration planning and design, climate change projections will ensure sustainability of the forest buffers and the benefits they provide. Key stages of project designs including establishing restoration goals and design criteria, evaluating design alternatives, and monitoring restoration outcomes should accommodate future climate and streamflow change. Further, planners may need to consider sites that are suitable for restoration under future conditions, as well as planting and invasive control methods that consider the impacts of climate change.

Rubin, J., McGranaghan, C., Kolba, L., & Görres, J. (2024). Restoring a Degraded Riparian Forested Buffer While Balancing Phosphorus Remediation, Biodiversity, and Indigenous Land Access. *Sustainability, 16*(8). doi:https://doi.org/10.3390/su16083366

This research tested whether mycorrhizae can rejuvenate the water quality and pollinator functions of degraded riparian forested buffers in agricultural landscapes while facilitating indigenous access to ancestral lands. This research revealed trade-offs between P

mitigation, indigenous use, and pollinator functions of the RFB. Fostering higher biodiversity, Indigenous land access, and P mitigation are important solution-oriented aims to balance when restoring degraded RFBs.

Saia, S. M. (2019). Applying climate change risk management tools to integrate streamflow projections and social vulnerability. *Ecosystems*, 67.

The research compared spatial distributions of subbasins at high risk of flooding based on SWAT results, SVI results, and the integration of SWAT and SVI results using a risk matrix. The risk matrix identified subbasins with vulnerable communities that are projected to experience future increases in streamflow due to climate and land use change. These results serve as a starting point for subsequent climate change adaptation planning.

Schilling, K. E., Li, Z., & Zhang, Y.-K. (2006). Groundwater–surface water interaction in the riparian zone of an incised channel, Walnut Creek, Iowa. *Journal of Hydrology, 327*, 140– 150.

Riparian zones of incised channels can potentially be a source of nitrate to streams during spring recharge periods when the near-stream riparian zone is largely unvegetated. Surface and groundwater interaction in the riparian zone of an incised stream during a spring high flow period was evaluated using detailed stream stage and hydraulic head data from six wells, and water quality sampling.

Schultz, R., Isenhart, T., & Simpkins, W. (2004). Riparian forest buffers in agroecosystems – lessons learned from the Bear Creek Watershed, central Iowa, USA. *Agroforestry Systems, 61*, 35–50.

Numerous variations of that design using trees, shrubs, native grasses and forbs or nonnative cool-season grasses may provide better function for riparian forest buffers in specific settings. Properly designed riparian buffers have been shown to effectively reduce surface NPS pollutant movement to streams and under the right geological riparian setting can also remove them from the groundwater. Flexibility in design can also be used to produce various market and nonmarket goods. Design flexibility should become more widely practiced in the application of this agroforestry practice.

Seavy, N. E., Gardali, T., Golet, G. H., Griggs, F. T., & Howell, C. a. (2009). Why Climate Change Makes Riparian More Important than Ever: Recommendations for Practice and Research. *Ecological Restoration*.

There is pressing need to develop a place-based understanding of climate change threats to riparian ecosystems. Practitioners should consider how to modify practices to enhance the resilience of riparian ecosystems to climate change.

Smith, M. M., Bentrup, G., Kellerman, T., MacFarland, K., Straight, R., & Ameya, L. (2021). Windbreaks in the United States: A systematic review of producer-reported benefits, challenges, management activities and drivers of adoption. *Agricultural Systems, 187*. doi:https://doi.org/10.1016/j.agsy.2020.103032

U.S. farmers value windbreaks primarily for indirect economic benefits and windbreak satisfaction is high among U.S. producers (72–99%). Lack of land and windbreak upkeep are the primary reasons for non-adoption, while poor condition, age, and conflict with farming practices drive windbreak removal. Survey research on windbreak management, costs, and marketable products is needed.

Sonenshine, D. E., 2018. Range Expansion of Tick Disease Vectors in North America: Implications for Spread of Tick-Borne Disease. Int. J. Environ. Res. Public Health, 15(3), p. 478.

Ticks have been expanding their geographic ranges in recent decades largely due to climate change. Furthermore, tick populations in many areas of their past and even newly established localities have increased in abundance. In this review, the geographic status of four representative tick species are discussed in relation to these public health concern. Both biotic and abiotic factors that may influence future range expansion and successful colony formation in new habitats are discussed.

Stanek, E. C., Lovell, S. T., & Reisner, A. (2019). Designing multifunctional woody polycultures according to landowner preferences in Central Illinois. *Agroforest Syst, 93*, 2293-2311. doi:https://doi.org/10.1007/s10457-019-00350-2

Multifunctional woody polycultures (MWPs) integrate fruit, nut, timber, and/or bioenergy crops adjacent to annual crops. The study findings demonstrate that a lack of reliable

economic, marketing, and management information severely constrains the adoption potential of MWPs despite landowner interest in using MWPs on marginal lands.

Thomas, K., & Nisbet, T. (2007). An Assessment of the Impact of Floodplain Woodland on Flood Flows. *Water and Environment Journal, 21*(2), 114-126.

Forested riparian buffers and floodplain woodlands can delay and reduce overall flood peak and reduce flow velocity. The delaying effect on flood flows is mainly due to the contribution of vegetation roughness. When considering species for buffer restoration, trees create more of a physical barrier than bushes because the latter can flatten during high flows whereas trees do not. The spacing and layout of trees, smoothness of trunks, presence of lower branches, level of undergrowth and amount of dead wood on the woodland floor all have an effect. Delaying the flood peak can extend the time available for flood warnings and could help desynchronize the flood hydrograph depending on where the woodland floodplain is located in the watershed. However, decreasing velocity on the floodplain actually increased velocity within the channel. This flow could be dissipated by other in-channel structures like woody debris dams.

USDA. (2023, November 15). *USDA Unveils Updated Plant Hardiness Zone Map*. From Agriculture Research Service: https://www.ars.usda.gov/news-events/news/research-news/2023/usda-unveils-updated-plant-hardiness-zone-map/

In 2023, the U.S. Department of Agriculture (USDA) released an updated Plant Hardiness Zone Map (PHZM), developed jointly by Agriculture Research Service (ARS) and Oregon State University's (OSU) PRISM Climate Group. Updated for the first time since 2012, the map is based on 30-year averages of the lowest annual winter temperatures at specific locations, is divided into 10-degree Fahrenheit zones and further divided into 5-degree Fahrenheit half-zones. Plant hardiness zone designations represent what's known as the "average annual extreme minimum temperature" at a given location during a particular time period (30 years, in this instance).

USDA. (n.d.). *Climate Hubs, Ecosystem Services*. Retrieved October, 2024 from United States Department of Agriculture: https://www.climatehubs.usda.gov/ecosystem-services

Ecosystem services are the direct and indirect benefits that ecosystems provide humans. They are typically broken down into four categories: provisioning services, regulating services, supporting services, and cultural services. A changing climate has the potential to alter many of the ecosystem services that are provided by and support agricultural and forestry systems, including food production, pollination services, pest control, and water quality regulation. Managing for adaptation and resilience can help stabilize production yields and maintain the suites of additional ecosystem services we receive.

US Environmental Protection Agency. (2025, January 15). *Climate Change Indicators: Stream Temperature*. From https://www.epa.gov/climate-indicators/climate-change-indicators-stream-temperature

From 1960 through 2014, water temperature increased at 79 percent of the stream sites measured in the Chesapeake Bay region. Since 1960, the Chesapeake Bay region has experienced an overall increase in stream water temperature. Temperature has risen by an average of 1.2°F across all sites and 2.2°F at the sites where trends were statistically significant. The largest increases have occurred in the southern part of the region.

Vose, J. M., Peterson, D. L., Domke, G. M., Fettig, C. J., Joyce, L. A., Keane, R. E., . . . Halo, J. E. (2018). Forests. In D. C. Reidmiller (Ed.), *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (pp. 232-267). Washington, DC. doi:10.7930/NCA4.2018.CH6

This report was developed as part of a mandate established by the Global Change Research Act of 1990, and was written to help inform decision-makers, utility and natural resource managers, public health officials, emergency planners, and other stakeholders by providing a thorough examination of the effects of climate change on the United States. In summary, it is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances and that climate change will decrease the ability of many forest ecosystems to provide important ecosystem services. The future pace of adaptation will depend on how effectively social, organizational, and economic conditions support implementation of forest management activities that increase resilience of forests to climate change.