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Buffer Options for the Bay: Exploring the Trends, the Science, and the Options of Buffer Management in the Great Bay Watershed Key Findings from Available Literature

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BUFFER OPTIONS FOR THE BAY: EXPLORING THE TRENDS, THE SCIENCE, AND THE OPTIONS OF BUFFER MANAGEMENT IN THE GREAT BAY WATERSHED

KEY FINDINGS FROM AVAILABLE LITERATURE

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We would like to recognize the invaluable support offered by the New Hampshire Association of Natural Resource Scientists, particularly Rick Van de Poll and Mary Ann Tilton at the New Hampshire Department of Environmental Services, in assembling this literature review. The data provided by NHANRS played a foundational role in crafting this review. We would also like to thank the members of the Buffer Options for the Bay project team and advisory committee for their key feedback in guiding the framework and development of this review.

A. Executive Summary

In New Hampshire, the need for trusted, relevant science is experienced at every scale of buffer management, from decisions made by property owners at the water's edge to those of state agencies setting policy for what is permissible on that land. Underpinning each decision are a series of tradeoffs that reflect assumptions held about the impact of that choice on the environment, the economy, and the well-being of the community. This literature review seeks to support these decisions and ground truth those assumptions by presenting a synthesis of available science on the subject of buffer management for the Great Bay Estuary (GBE) and its tributaries in southeast New Hampshire.

The review was commissioned by the Buffer Options for the Bay ("BOB") technical team, which is a component of the larger integrated assessment BOB project entitled "Exploring the Trends, the Science, and the Options of Buffer Management in the Great Bay Watershed." Buffer Options for the Bay is a grant-sponsored collaboration of public, academic, and nonprofit organizations dedicated to enhancing the capacity of New Hampshire stakeholders to make informed decisions that make best use of buffers to protect water quality, guard against storm surge and sea level rise, and sustain fish and wildlife in the Great Bay region. In keeping with this goal, this review has been inspired by typical questions that arise in the course of local buffer management. For example, what role do buffers play in protecting water quality? In mitigating the impacts of flooding and sea level rise? Providing habitat for protected or commercially important wildlife? Enhancing property values? What does the science suggest we do to ensure that buffers can continue to support these services? How much are people "willing to pay" to maintain or avoid loss of these functions?

To help address these questions, this review considered both primary literature and previous literature reviews. The latter includes recent work undertaken by the New Hampshire Association of Natural Resource Scientists, as well as studies by Sweeney and Newbold (2014), Washington State Department of Ecology (Sheldon et al. 2005), Rhode Island Division of Planning (Metz and Weigel 2013), New Hampshire Audubon (Chase et al. 1995), University of Georgia (Kirwan and Megonigal 2013; Wenger 1999), Environmental Law Institute (Environmental Law Institute 2008), and Good Forestry in the Granite State Steering Committee (Bennett 2010). There is an incredible volume of scientific literature relevant to the topic of buffers, and our intention was not to be exhaustive in this review; instead we focus on the most locally relevant science that can be used to address the aforementioned questions in New Hampshire.

From this review, we found that while the best available science provides clear guidance to inform decision-making related to buffer management in New Hampshire, research questions remain. For example, it is clear that buffers can help protect many of the benefits that the GBE and its tributaries provide to surrounding communities such as recreational opportunities and healthy fisheries. This capacity, however, depends on a buffer's particular attributes, including its width, a characteristic of critical importance to all stakeholders and a topic that has received considerable attention in the peer-reviewed literature. While many papers make recommendations for buffer width, these studies often seek to address how wide a buffer would need to be to maintain the types of ecological features or functions found in entirely natural landscapes, such as an assemblage of forest-associated birds. Consequently, they tend to focus on relatively wide margins of land that may not be practical, or even feasible, in some settings. While it is critically important that we understand these minimum widths and hence what aspects of the environment will be degraded with narrower buffers, it is also important that we understand what functions might be provided by the narrower buffers that may be the only feasible option in certain settings. Relatively few studies have focused on the topic of narrower buffers, with the exception of research on nutrient removal. As a result of the limited data on narrower buffers, this review puts forward minimum buffer width recommendations based on what is necessary to maintain buffer functions, with the caveat that we do not always fully understand how well narrower buffers may function. These recommendations are supported by pertinent examples of specific analyses from the literature.

In addition to the limited data available to help in understanding the role of narrow buffers, a challenge also exists in quantifying a direct relationship between the restoration, maintenance, or loss of buffers in real-world scenarios and a corresponding change in the focal ecosystem service. Most primary research on buffer efficacy is conducted under controlled conditions within the confines of a research project. Under this approach, unwanted variability in the environment is minimized in order to test specific hypotheses. However, when buffers are utilized in practice, there is typically considerable variability in the environment, accompanied by a lack of replication – for example, often a single watershed is evaluated. This makes the type of statistical analyses deployed in experimental research difficult. Understanding this challenge is important, as it can lead to a conclusion that, in practice, buffers are not as effective as indicated by most primary research. However, the reality is that the findings of primary research hold true, i.e. buffers can be an effective tool, but the variability of complicating factors in the natural environment can either mask or override the role that buffers play in influencing ecosystem services.

The science synthesized in this document is intended to be used by the BOB project team, although the explicit intent is to then create a number of informational products that translate this science into a more accessible form for end users. Ultimately, the products that are shaped from this review will be of service to all buffer management stakeholders in the Great Bay region, including landowners and the consultants who work with them, regulatory agencies and municipalities, conservation organizations and foundations, and scientists interested in conducting research that will lead to more effective buffer management.

Science, however, is only one piece of the buffer management puzzle. To augment this review, the BOB collaborative has conducted an analysis of regulatory and non-regulatory policy options for New Hampshire, an economic analysis of the values placed on the water quality benefits provided by buffers, a buffer-focused GIS analysis of the GBE region, and an assessment of the barriers and opportunities related to buffer management at the community level in the Exeter/Squamscott subwatershed.

The results of these analyses have been captured in individual reports. They've also been integrated into a framework intended to inform discussions around buffer management, restoration, and protection in the GBE region. We anticipate that this framework will open the door to new and needed research; strategic and complementary investments by state agencies, nonprofits, and foundations; and a collective strategy for outreach professionals to work with towns on advancing effective buffer policy and practice at the community level.

B. WHAT IS A BUFFER?

Before embarking on a review of scientific information relating to buffers, it is important to understand what is meant by this concept. Such understanding is confounded by the range of terminology used in relation to buffers. Two or more terms may be used to refer to what is essentially the same concept, or the same term may be used in different contexts with different underlying meanings. This can lead to confusion that hinders effective buffer management.

For the purpose of this review, *buffer* is defined as an upland area adjacent to wetlands (Sheldon et al. 2005), and *wetland i*s defined as a transitional zone between terrestrial and aquatic habitats that includes landscape features that contain or convey water and support unique plants and wildlife (Environmental Law Institute 2008)[1]. Using these definitions, examples of wetlands could include streams, rivers, ponds, lakes, bogs, and vernal pools. This review is focused on the Great Bay Estuary (GBE) region, and is therefore concerned primarily with coastal buffers (i.e. the boundary adjacent to tidal waters of the estuary), buffers adjacent to streams and rivers that flow into the bay, and buffers adjacent to wetlands that are hydrologically connected to the waters of the bay. The terms listed below are often used, sometimes interchangeably, when referring to areas that fit the aforementioned description of buffers.

- Buffer
- Vegetated filter strip
- Buffer strip
- Riparian area
- Riparian zone
- Riparian corridor

While each of these terms may be more commonly employed in different arenas (e.g. regulation/policy versus ecological condition or location), or more typically associated with a certain definition, there is considerable mixing of usage. Given that the BOB project is not focused on any single specific function of buffers, we use 'buffer' throughout this document in reference to the range of functions that may be encompassed by all of the terms listed above.

[1] One's understanding of the term 'buffer' is often informed by one's background or experience. A planner or developer may consider buffers to be defined regulatory areas in which development may be constrained. A scientist or ecologist may have a much broader and less rigid understanding, characterized more by the ecological setting, form, and function than by a simple regulatory boundary.

In addition to the variation in terminology, a considerable range of definitions are used in reference to buffers. Perhaps the simplest is "*the uplands adjacent to wetlands*" (Environmental Law Institute 2008), i.e. a strictly spatial definition. However, the concept of a buffer is more typically applied to describe a range of land management practices in these upland areas. These practices can range from restricting activities from within a specified distance from a water body (also commonly termed a 'setback') to complex recommendations for habitat management designed to protect specific groups of organisms or functional roles. For example, Reed (2013) defined buffers as "*vegetated strips of land separating runoff- and pollutant-contributing areas from surface waters*." Similarly, Chase et al. (1995), defined a buffer as "*a naturally vegetated upland area adjacent to a wetland or surface water*." Conversely, Semlitsch and Jensen (2001) recommended the following nuanced description for amphibians and reptiles:

"*We propose the use of stratified criteria that would include at least three terrestrial zones adjacent to core aquatic and wetlands habitats: (1) starting from the wetland edge, a first terrestrial zone would buffer the core aquatic habitat and protect water resources; (2) starting again from the wetland edge and overlapping with the first zone, a second terrestrial zone would comprise the core terrestrial habitat defined by semi-aquatic focal species or species-group use; and (3) starting from the outward edge of the second zone, a third terrestrial zone would buffer the core terrestrial habitat from edge effects and surrounding land-use practices.*"

Bearing in mind this range of definitions, in general, the term 'buffer' is used to denote a specified area of upland habitat adjacent to streams, rivers, ponds, lakes, and/or other wetland types, typically associated with maintaining or promoting one or more ecological or socio-economic functions, and with specific land use regulations implemented within this area to meet these objectives. These land use practices can either be activities that are prohibited, such as construction, or encouraged, such as maintenance of natural vegetation. In the ecological literature, the term 'buffer' generally relates to the naturally vegetated zone adjacent to wetlands and precludes consideration of gray infrastructure (i.e. storm sewers, culverts, pipes, other human-engineered systems) that might serve some of the same functions as green or natural infrastructure (i.e. forests, wetlands, other natural ecosystems).

'Setback' and 'jurisdictional zone' are two terms that are often used in similar contexts as buffers – specifically, regarding the regulatory capacity for water body protection. However, setbacks and jurisdictional zones are distinct from buffers. These terms will not be covered in depth in this review, but the following background information is provided to help differentiate setbacks and jurisdictional zones from buffers.

Much like 'buffer,' the term 'setback' has a range of definitions. A setback is generally a specified distance from the water body within which certain activities are restricted, such as building construction or establishment of a septic system. Wetland setbacks are not necessarily naturally vegetated, as setbacks are typically aimed specifically at maintaining water quality rather than the broader goals often targeted by buffers. However, the term 'setback' is sometimes used interchangeably with 'buffer.' An example of one definition is "*a distance requirement from certain activities*," from New Hampshire Department of Environmental Services (NHDES). As another example, the National Oceanic and Atmospheric Administration defines a setback as "*a distance landward of some coastal feature (e.g. the ordinary high water mark within which certain types of structures or activities are prohibited*" (Lemieux et al. 2004).

A jurisdictional zone is another area in which restrictions may be set to protect a water body. A jurisdictional zone is generally the boundary extending out from a water body to which a governing agency (i.e. state and/or municipality) has regulatory capacity. With respect to buffers, a jurisdictional zone typically includes and extends beyond buffer and setback widths. The NHDES Wetlands Bureau defines a jurisdictional zone as "*an area that is subject to regulation under RSA 482-A [Fill and Dredge in Wetlands], as described therein.*" An illustration of the typical spatial arrangement of buffers, setbacks, and jurisdictional zones is provided in Figure 1 below.

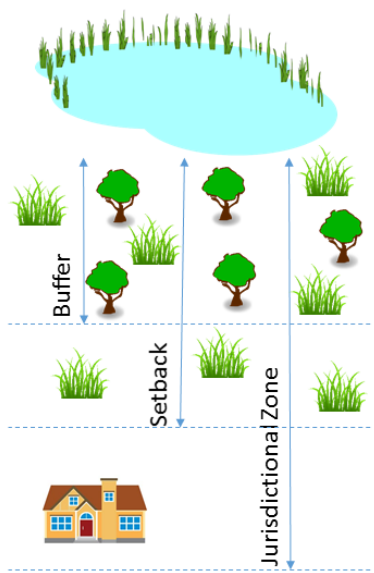


Figure 1. Conceptual illustration of buffer, setback, and jurisdictional zone extents in relation to the water body (not to scale).

C. Which environmental issues do we hope to address through the use of buffers in the Great Bay Estuary (GBE)?

The principal threats to the Great Bay Estuary (GBE) are well summarized in the Piscataqua Region Estuaries Partnership's (PREP) 2013 State of Our Estuaries Report (PREP 2013) and the Great Bay Non-Point Source Study (Trowbridge et al. 2014). These documents and the resources they draw upon describe a complex range of interrelated stressors that have led to ecological degradation and associated socio-economic costs, including terrestrial pollutants from settlements and agriculture, changes in sedimentation, changes in water temperature and levels of dissolved oxygen, loss of natural habitat due to land conversion (Fig. 2a, Fig. 2b), declines in oyster reefs and eelgrass beds, increases in invasive aquatic species and nuisance native macroalgae, altered flow regimes and barriers to the passage of aquatic organisms between marine and freshwater environments, increased flooding and erosion, and sea level rise. Buffers have the potential to help in ameliorating all of these issues with the exception of invasive species, aquatic organism passage for strictly aquatic species, sea level rise, and changes in estuarine water temperature as a result of ocean warming.

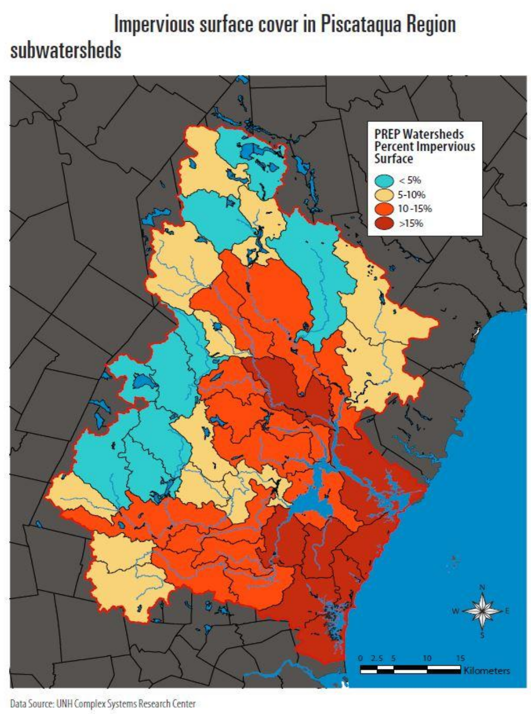


Figure 2a. Impervious surface cover trends in the Great Bay Estuary region. Provided by Piscataqua Region Estuaries Partnership (PREP 2013).

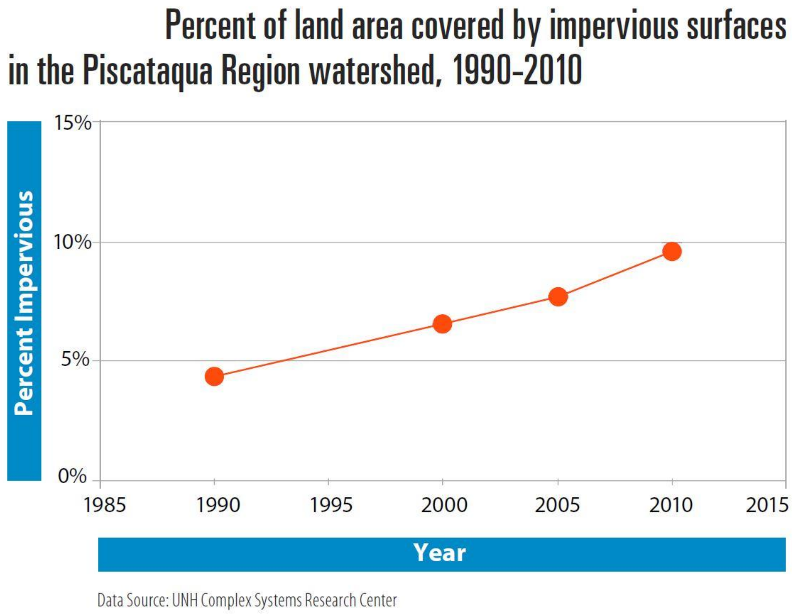


Figure 2b. Impervious surface cover trends in the Great Bay Estuary region. Provided by Piscataqua Region Estuaries Partnership (PREP 2013).

Nitrogen/nutrient loading and sediment inputs to the GBE remain significant drivers of ecological degradation, with high inputs facilitated by the increasing amount of impervious cover and loss of natural cover within the watershed (Trowbridge et al. 2014). Excess nutrient inputs to aquatic systems reduce water quality and decrease species richness. Sixty-eight percent of the nitrogen in the GBE system comes from nonpoint sources spread across the watershed, with the remainder coming from municipal wastewater treatment discharge. Nonpoint sources include atmospheric deposition, fertilizers, human waste from septic systems, and animal waste. Human waste from septic systems contributes 29 percent (~240 tons/year) of nitrogen inputs to the GBE and is the largest nonpoint load after atmospheric deposition (42 percent). Thirty-four percent of nonpoint source loads were delivered through stormwater (surface water of abnormal quantity resulting from heavy rains or snowfall).

The loss of buffers is particularly important in the context of nutrient and sediment inputs. Nitrogen inputs are closely linked to levels of dissolved oxygen (DO): In general, the tidal mixing in the GBE means that levels of DO are above minimum water quality standards of 5 mg/L. However, tidal rivers flowing into the GBE regularly fall below this threshold, posing a risk to aquatic organisms (PREP 2013). Suspended sediments continue to increase in the GBE, having risen by 12 percent from 1976 to 2011. These suspended sediments result from both wave/tidal disturbances to estuarine silts, and run-off delivery of terrestrial sediments into the bay (i.e. a combination of resuspension of existing sediments in the bay, and increased terrestrial inputs). These threats from nutrient and sediment inputs can be ameliorated by the use of buffers.

Increased nutrient levels, coupled with sedimentation and disease outbreaks, are likely to be important contributors to declines of eelgrass and oyster reef areas within the bay (Fig. 3). Historically, there were approximately 1,000 acres of oyster reefs in the GBE, with only ~10 percent of this area now remaining (PREP 2013). Similarly, eelgrass beds once dominated nearshore habitat in the bay, but their distribution has declined by 44 percent since 1996, and their biomass has decreased by 79 percent (Short 2016). The loss of these habitats is particularly notable given the important ecological functions they provide. These include water filtration by oysters, important habitat for juvenile fish and aquatic invertebrates, and estuarine sediment trapping. As these habitats have declined, there is the potential for a feedback mechanism wherein the increased sedimentation and decreased water quality partially resulting from oyster and eelgrass declines creates conditions in which it is harder to restore these same habitats. In addition to this ecological functionality, oysters and seagrass meadows are commercially valuable. For example, a study of Mediterranean seagrass meadows estimated they were annually worth $119 million for commercial fishing (Jackson et al. 2015).

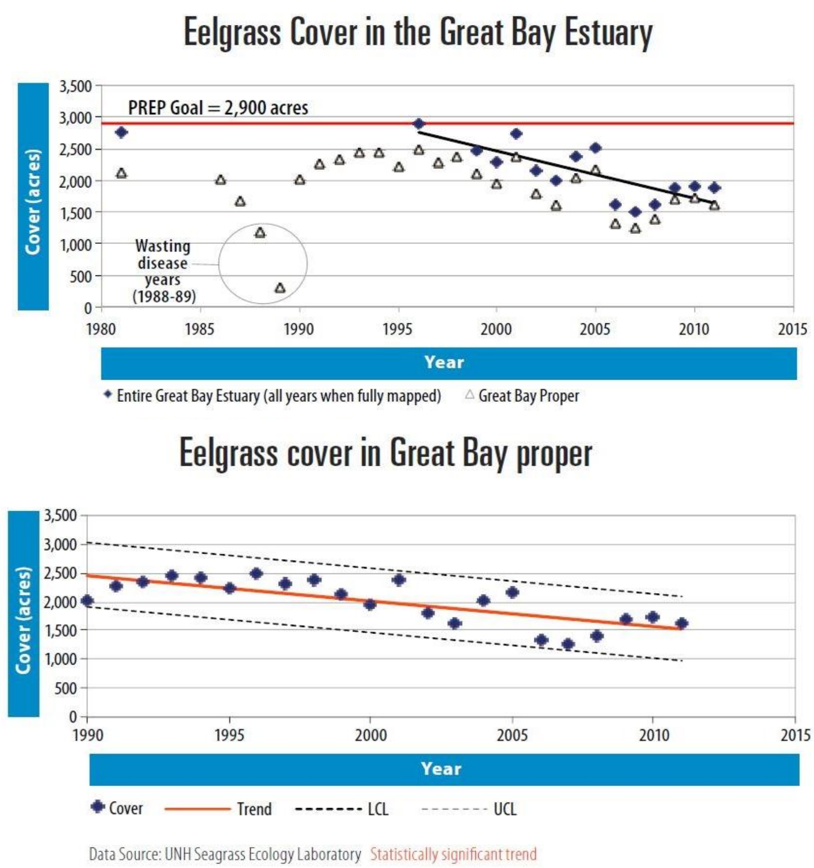


Figure 3. Eelgrass cover trends in the Great Bay Estuary region. Provided by Piscataqua Region Estuaries Partnership (PREP 2013).

Widespread conversion of natural habitats has been deemed the leading cause of biodiversity loss worldwide. Riparian habitat is at particular risk from conversion as these areas are often highly suitable for agriculture and desirable locations for human development. In the United States, ~1 percent of riparian areas were lost from 1972 to 2003 (Pusey and Arthington 2003). While this figure may not seem high, it is important to recognize that this represents a continued loss of habitat on top of historical loss in many places. In coastal New Hampshire, much of this land conversion can be attributed to a growing human population as a result of proximity to the expanding greater Boston area. From 1990 to 2010, the population in the region grew by 19 percent with a concomitant 120 percent increase in impervious cover (representing 9.6 percent of the land area). The loss of buffers is of particular concern given that they support a wide range of organisms associated with both terrestrial and aquatic habitats (Naiman et al. 1993) and are thought to provide connectivity, i.e. allow movement of organisms across the landscape, particularly in situations where upland habitat adjacent to the buffer has been lost (Machtans et al. 2002, Beier and Noss 2008).

In addition to habitat loss, conversion of riparian habitat increases the load of stressors such as nutrients and sediment with little opportunity for ameliorating these threats before they enter wetlands. Areas close to waterways contribute a significant proportion of inputs (~10 percent of nitrogen loading comes from within ~650 ft. of waterways) (PREP 2013). As an example of the consequences of conversion, research in the NH Seacoast region found that water quality and biological conditions in-stream declined as the percentage of urban land increased within an ~80 ft. buffer (Deacon et al. 2005).

Sea level rise (SLR) is also a significant threat to the GBE. While sea levels are rising in many areas of the world as a result of melting polar ice caused by global climate change, the northeastern United States has been identified as a hotspot of accelerated SLR, with rates 3 to 4 times higher than global averages (Sallenger et al. 2012). SLR will lead to extensive coastal flooding (Kirshen et al. 2008), and may lead to the loss of important coastal habitat, such as dunes and salt marshes, depending on the rate of SLR and ability of habitats to redistribute in response to these changes (Craft et al. 2008). The high density of human settlement and associated infrastructure in lowland areas adjacent to the GBE also puts many communities at significant risk of coastal flooding as a result of SLR (Hamilton et al. 2010).

D. How might buffers address these issues?

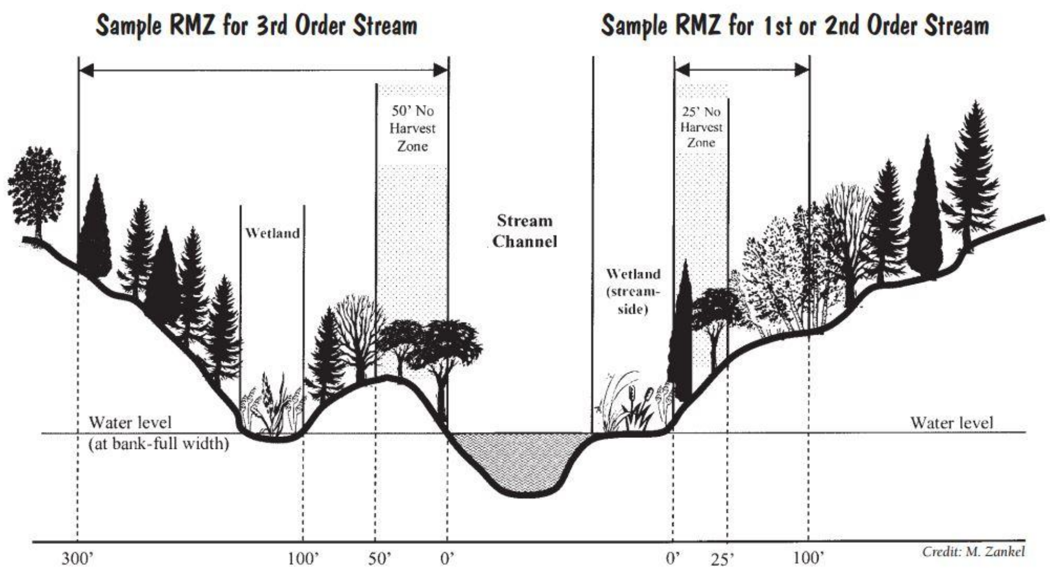
Buffers can provide a range of ecological benefits to help in ameliorating the threats listed above (summarized in Table 2 with a more detailed narrative description provided in the following sections). However, before describing the role of buffers, it is important to recognize that the provision of these services is highly dependent on both the wider landscape within which the buffer is found and the localized context of the buffer itself (Wenger 1999, Franzen et al. 2006, Bardgett et al. 2013, Raney et al. 2014). Landscape context is particularly important as it will influence the nutrient loading that the buffer will intercept. For example, if a buffer is situated in close proximity to a large area of commercial development, there is likely to be a higher loading of contaminants compared to a largely forested watershed. Similarly, the functioning of the buffer will be influenced by a range of characteristics including vegetation, width of the buffer, slope, and underlying soils. We have attempted to discuss these topics throughout this literature review, but an in-depth discussion of topics such as the linkage between watershed management, land-use change, and nonpoint source pollution is beyond the scope of our analyses.

Research has shown that the effectiveness of pollution reduction by 'green' infrastructure, or natural areas that provide ecosystem services (in this case, buffers), is not only comparable to that achieved by 'gray' infrastructure (constructed stormwater interventions), but that green infrastructure typically costs markedly less (Talberth et al. 2012). As watersheds have degraded over time, costs for traditional water treatment have doubled for about one in three large cities globally (McDonald et al. 2016). Specifically, from 1900 to 2005, 90 percent of urban source watersheds experienced some watershed degradation, with the average pollutant yield of urban source watersheds increasing by 40 percent for sediment, 47 percent for phosphorus, and 119 percent for nitrogen (McDonald et al. 2016). By electing to use natural/green infrastructure such as buffers and wetlands, stakeholders avoid watershed degradation. This avoidance in turn helps maintain water quality and reduces treatment costs, as the natural capital of natural land cover functions as an alternative to investment in gray infrastructure (McDonald et al. 2016). As an example of the comparison between green and gray infrastructure, building a wastewater treatment system using constructed wetlands costs around $5 per gallon of capacity compared to approximately $10 per gallon of capacity for a conventional advanced treatment facility (Foster et al. 2011). Additionally, green infrastructure is estimated to be three to six times more effective in managing stormwater per $1,000 invested than conventional methods. For example, the largely intact floodplains and wetlands within Vermont's Otter Creek watershed were estimated to have reduced damage by 54 to 78 percent across ten flood events to the town of Middlebury, and by 84 to 95 percent for Tropical Storm Irene (Watson et al. 2016). The annual value of these flood mitigation services exceeded $126,000 and may be as high as $450,000. Green infrastructure also functions better than gray infrastructure in climate adaptation and resilience by providing a suite of co-benefits, such as improving air quality, reducing urban heat effects, lowering energy demand, and even increasing land values by up to 30 percent (Foster et al. 2011).

Before considering the extent to which buffers can help support specific ecosystem services, it is important to address the overarching topic of buffer width. This theme has received considerable research attention, with a number of review papers offering recommendations for different objectives (e.g. Lee et al. 2004; Kirwan and Megonigal 2013). It is worth noting, however, that studies have tended to focus on relatively wide buffers that may not be feasible in some settings, such as areas where high development pressure impedes the ability to establish buffers of the recommended width.
As a consequence, there is some concern that the efficacy of narrower buffers may not be well understood (Hickey and Doran 2004).

This review provides fixed width buffer recommendations, but we recognize the utility of variable buffer width recommendations as well. Variable width buffers are buffers that do not maintain a uniform width throughout their extent (Fig. 4, Table 1). Variable width buffers can provide an important tool for meeting an ecosystem service target (for example, removal of nutrients), but where it is infeasible to maintain or restore a fixed width buffer. Examples of factors that preclude the use of a fixed width buffer can include adjacent land use, site and stream conditions (i.e. topography, soil, hydrology) and places where buffers have been lost and restoration is not feasible (Environmental Law Institute 2003; Aunan et al. 2005). For example, in places where habitat loss has already led to a fragmented or asymmetrical buffer, greater widths will be needed in remaining habitat to maintain buffer integrity (i.e. for the buffer to provide the same level of ecosystem services) (Barton et al. 1985). Variable width buffers, specifically larger widths, may also be employed to protect pristine or highly-valued riparian areas; areas close to high-impact land use activities; or areas with steep banks, sparse vegetation, or highly erodible soils (Environmental Law Institute 2003).

A recent review undertaken by the New Hampshire Association of Natural Resource Scientists (NHANRS) employed a comprehensive literature review to focus specifically on the topic of buffer widths. Given the overlap between our review and the work of NHANRS (both focusing on buffers in the state of New Hampshire), we have summarized available recommended minimum buffer widths to achieve different objectives at the end of each section below and in Table 3. One can reference the NHANRS review for a complete list of the studies from which these recommendations were drawn (Appendix 1, Appendix 2, Appendix 3).



The left side of the illustration shows the recommended RMZ for a 3rd order stream. The right side shows the recommended RMZ for a 1st or 2nd order stream. Note that the RMZ on the right side is measured from the upland edge of the streamside wetland. If there is no wetland at the edge of the stream, the RMZ is measured from the top of the streambank (at bankfull width). The disjunct wetland on the left side overlaps and is included within the RMZ.

Figure 4. Theoretical illustration of sample recommended riparian management zone (RMZ) delineations for streams of various orders, for the purpose of forest management. Reproduced from *Good Forestry in the Granite State* (Bennett 2010).

Table 1. Sample riparian management zone guidelines in New Hampshire for various water body sizes, for the purpose of forest management. Reproduced from *Good Forestry in the Granite State* (Bennett 2010).

	Legally Required		**Recommended**	
	Riparian Management Zone (ft.)	**No Harvest Zone (ft.)**	**Riparian Management Zone (ft.)**	**No Harvest Zone (ft.)**
Intermittent Streams	None	None	75	None
1st and 2nd Order Streams	50	None	100	25
3rd Order Streams	50	None	300	50
4th Order and Higher Streams	150	None	300	25
Pond (<10 acres)	50	None	100	None
Lake or Great Pond (>10 acres)	150	None	300	25

One caveat when interpreting the findings of different studies in regards to buffer width is that there was some variability in how the width of a buffer was determined based on what constituted the edge of the buffer. Given the abundance of studies focusing on buffer width, our sense is that this additional variability is unlikely to have strongly influenced recommendations, although the relevance of this issue increases when there are relatively few studies supporting specific guidance. The history of development and reforestation seen throughout New England, and particularly in coastal New Hampshire, means it is also important to note that in individual sites, buffer function may be influenced by prior alteration, such as where soils have been heavily modified by past agriculture.

Caveats aside, the overarching message regarding the relationship between buffer width and provision of ecosystem services is a simple one: in general, wider and more forested buffers provide greater benefits to water quality and biodiversity. Another key theme that emerged from research findings is the influence of landscape context on buffer efficacy, including factors such as topography, the location of stressor sources, and the underlying water table. Furthermore, longer, continuous buffers are more effective than fragments of greater widths for hydrologic functions, reducing gaps in maintaining water quality, and wildlife habitat (Fischer et al. 2000). Additionally, wider buffers may be warranted next to particularly sensitive resources (for example, impaired water bodies), and closer to the GBE, where there is less opportunity for excess nutrients that enter streams and rivers to be ameliorated before entering the bay, although research has shown that buffers along headwater streams that feed into a target water body have a greater influence on overall water quality than those directly surrounding that water body (Fischer et al. 2000). The following sections provide a more detailed summary of the state of current scientific knowledge regarding buffer width and the provision of specific ecosystem services. In Table 4, we offer a single recommended minimum buffer width for each specific ecosystem service drawn from our literature review. In addition to these recommendations, we have also compiled gaps in the best available science in Appendix 4 that, if addressed through further research, would improve the recommendations we are able to offer practitioners regarding the use of buffers. It is important to keep in mind that buffer width is one of several factors that determine a buffer's ability to provide a variety of services – considering buffer width alongside linear extent, vegetation composition, and level of permanent protection facilitates more holistic and effective buffer management.

While buffer width is an important indicator of how well a buffer may provide ecosystem services, the composition of the buffer is also a key factor in determining how well a buffer functions. Buffers that are naturally vegetated generally provide ecosystem services to a greater extent than buffers that are sparsely vegetated or have been cleared or altered, such as a forested buffer that has been converted to grass (Bentrup 2008, Castelle et al. 1992, Fischer and Fischenich 2000). To compare, nitrogen uptake and retention were significantly higher in forested buffer sites compared to herbaceous sites – a retention difference between 99 percent and 84 percent, respectively, in one study (Haycock and Pinay 1993, Hefting et al. 2005). Buffers consisting of native vegetation perform better when the vegetation is well-adapted to site conditions and diverse, so the buffer's vegetation captures a wide array of environmental tolerances that support a number of functions (Fischer and Fischenich 2000). The buffer is therefore better able to be resilient in the face of fluctuating environmental variables. When restoring buffers, this diversity can be achieved through utilizing an array of species, growth forms, and life histories. Overall, naturally vegetated, diverse buffers are more effective at reducing pollution into the water body than sparsely vegetated, homogenous buffers.

In summary, buffers can be employed to provide a variety of ecosystem services and mitigate a host of environmental issues, but the extent to which buffers deliver these functions depends greatly on the characteristics of the buffer itself as well as the larger landscape characteristics surrounding the buffer. A central metric in assessing the extent to which a buffer is providing certain functions is the width of the buffer. In the following sections, three overarching themes of ecosystem services that buffers provide – water quality, hydrologic effects, and habitat for biodiversity – are dissected. This analysis serves as an assessment of how buffers specifically deliver these functions and of what widths are generally adequate to provide these services.

I. Water Quality

Buffers contribute to the maintenance of water quality in a variety of often synergistic ways. For instance, sediment removal by buffers may also remove phosphorus bound to sediment particles. A number of studies have made general recommendations for the width of buffers needed to maintain overall water quality. The lowest recommendation is 16-foot. (Fischer and Fischenich 2000), although the majority of studies provide a minimum width of 100-foot (Appendix 1).

Most of the published research on the efficacy of buffers for promoting water quality has focused on naturally vegetated habitat, and it is from this body of work that our recommendations are drawn. However, setbacks that prevent certain land uses or structures, such as the installation of a septic system or construction of a building, within a certain distance from a water body can help to maintain water quality by reducing erosion, pollutant runoff, and runoff flow volume and velocity. The following section provides a detailed commentary regarding the role of buffers in helping to address specific components of water quality.

i. Reducing inputs of excess nutrients and contaminants

Implementing buffers has been shown to be an effective approach in reducing the transport of nitrate and phosphate from agriculture and development (Peterjohn and Correll 1984, Environmental Law Institute 2008). Nutrients are absorbed into the buffer sediment, taken up by plant biomass, and immobilized by microorganisms through denitrification (Hruby 2013). As phosphorus primarily enters buffers attached to sediments or as organic material (Wenger 1999), the role of the buffer in reducing inputs to wetlands conforms to the same mechanisms as that of reducing sediment inputs in general. Experimental research has demonstrated that even narrow grass buffers have the capacity to reduce phosphorus inputs. For example, a 15-foot (4.6 m) grass buffer strip removed 18 to 71.5 percent of total phosphorus (Wenger 1999). When increased to 31-foot (9.6 m), grass buffers removed 46 to 79 percent of phosphorus. In some cases, removal of phosphorus and nitrogen by buffers approached 90 to 100 percent (Hickey and Doran 2004).

One important caveat to these experimental findings is that the effectiveness of the buffers decreased over time, presumably due to previously-trapped phosphorus being re-mobilized (Wenger 1999) and soils becoming saturated by nitrogen (Woods Hole Group, Inc. 2007). It is also important to note that buffer effectiveness may vary *in situ*, since percent removals are dependent upon input load. Furthermore, the depth of the water table in relation to root biomass within the buffer likely plays an important role in influencing rates of nutrient and contaminant uptake (Marczak et al. 2010). Lastly, while grass buffers may effectively reduce nutrient inputs in certain settings, forested buffers may be more effective in providing a broader suite of ecosystem services. Bearing in mind these caveats, buffers with more hydric soil, flatter topography, and a higher water table are typically better able to remove pollutants. Based on models developed for the GBE, watershed conservation efforts (i.e. protection of wetlands and forests) could reduce nitrogen inputs to the bay from three to 28 metric tons per year (Berg et al. 2016).

Buffers are also capable of stabilizing other pollutants, although the buffer widths necessary for effective removal have not been as well-studied. Buffers can render pathogens harmless as they are carried in subsurface flow through the soil, neutralize acid deposited by acid rain through uptake into the forest canopy, and stabilize some metals through adsorption to soil particles (Chase et al. 1995). Furthermore, buffers provide filtration sufficient to trap fuel and lubricants from upslope land uses (Bennett 2010).

The following is a summary of the minimum recommended buffer widths necessary to provide reduction of excess nutrient and contaminant inputs. Much of the pollutant removal may occur within the first 15 to 30 feet of a buffer, but buffers ranging from 30 to 100 feet or more will remove pollutants more consistently (Environmental Law Institute 2008). Based on available literature, the minimum buffer width needed for effective reduction of nitrogen is 60 feet. (Correll and Weller 1989), and the majority of sources recommend a width of at least 98 feet (Appendix 1). The minimum buffer width for effective reduction of phosphorus is 30 feet. (Fischer and Fischenich 2000), and the majority of sources recommend a width of at least 98 feet. (Appendix 1).

ii. <u>Mediating sediment</u>

Buffers can help to reduce issues associated with sediments in three ways: (1) preventing the occurrence or mediating the severity of sediment-producing activities, such as construction or agriculture close to the wetland edge; (2) trapping terrestrial sediments carried in run-off before they enter the wetland; and (3) supporting in-stream conditions that increase sediment deposition and/or reduce erosion, such as reducing the severity of high flow/velocity events from storm flows, stabilizing banks, and contributing woody debris, which traps sediments in the water (Mayer et al. 2007, Liu et al. 2008, Zhang et al. 2010, Kirwan and Megonigal 2013). Since nutrients are often bound to sediment particles, the reduction of sediment transport may also serve to reduce nutrient export from riparian zones (Hickey and Doran 2004). For instance, sedimentation may account for phosphorus retention rates of up to 115 lb/acre/year (Hoffman et al. 2009). Sediment retention is also an important factor in maintaining viable foraging and spawning sites for fish and other aquatic organisms (Chase et al. 1995, Hickey and Doran 2004).

The role of buffers in reducing sediment inputs can be profound (Young et al. 1980, Dillaha et al. 1988, Dillaha et al. 1989, Magette et al. 1989). For example, experimental research demonstrated that a 54-foot buffer consisting of switchgrass and woody vegetation (shrubs and trees) removed 97 percent of the sediment from an adjacent field (Polyakov et al. 2005). Similarly, researchers found that ~65 percent of sediments were trapped by a 33-foot streamside forest buffer and ~85 percent for a 66-foot buffer (Sweeney and Newbold 2014). It is also worth noting that landscape models indicated a high percentage (47 percent) of the total variation in sediment loading to streams could be explained by riparian forest cover, highlighting the importance of buffers in mediating sediment transfer (Jones et al. 2001). While one study found that narrow buffers (16 to 66-foot) are able to remove coarse sediments, wider buffers (66 to 328-foot) are better able to remove finer sediments (Hruby 2013). The minimum buffer width for effective sediment removal is 30 feet (Environmental Law Institute 2008), and the majority of sources recommend a width of at least 98 feet (Appendix 1).

iii. <u>Influencing water temperature</u>

In freshwater systems, vegetated buffers help to regulate stream temperatures by providing shade (Hruby 2013). This is particularly important for cold-water fish, as increases in water temperature also have potentially undesirable effects on stream chemistry, aquatic insects, stream flora, and fish behavior and development (Hagan and Whitman 2000). For example, average stream temperatures increased by 7.9°F after the removal of riparian forest, and there was an 18°F increase in maximum temperature between a clear-cut stream and a buffered stream (Rishel et al. 1982). Furthermore, streams with vegetation removed tend to experience summer temperature increases of 9° to 19.8°F above streams where natural vegetation was maintained (Bentrup 2008). Based on these findings, buffer widths ranging from 25 to 100 feet have been proposed for adequate water temperature modification (Barton et al. 1985, Bentrup 2008, Osborne and Kovacic 1993), with a recommended minimum of 30 feet based on a synthesis of available literature (Wenger 1999).

iv. <u>Providing organic inputs into aquatic systems</u>

Buffers contribute leaf litter, detritus, small woody debris, and insects to adjacent aquatic ecosystems. These important energy inputs drive aquatic ecosystem food webs (Naiman et al. 2002, Fisher and Likens 1972, Golladay et al. 1992, Wallace et al. 1997). Larger coarse woody debris inputs into streams and rivers are important for creating the range of different environments required by organisms for shelter, foraging, hibernation, and reproduction, including pools, riffles, debris jams, and related structural aquatic habitat (Chase et al. 1995, Fischer and Fischenich 2000). They also help to retain sediments and nutrients, and influence channel morphology (Naiman et al. 2002). Reid and Hilton examined how wide buffers would need to be to maintain tree-fall rates similar to those in undisturbed forest and to provide coarse woody debris to the riparian area. They recommended a buffer width of 4 to 5 tree heights, with a tree height being defined as the average maximum height of the tallest dominant trees (200 years or older) for a given site class (Reid and Hilton 1998). Similarly, Bentrup (2008) recommended a buffer width from 100 to 400 feet for adequate woody debris and litter input. Based on a summary of the available literature, Wenger (1999) recommended a minimum buffer width of 50 feet to provide sufficient woody debris to streams.

II. Hydrologic Effects

Buffers provide a range of hydrologic ecosystem services that may be particularly important given evidence of the increasing frequency of "extreme" weather events. Total annual precipitation in the northeast United States has increased over the past century, with intense storm events occurring with more frequency (Smith et al. 2008b). As of 2008, the cost of repairing damages from flooding and fluvial erosion was $6 billion per year in the United States; this has likely increased since then (Smith et al. 2008b). Vegetated buffers reduce the severity of flood events by intercepting overland flow from precipitation and meltwater and by allowing for greater infiltration. The majority of studies focusing generally on the hydrologic ecosystem services provided by buffers have recommended a width of 98 feet to maintain these services (Appendix 2), with a minimum recommendation of 33 feet (Wenger 1999, Fischer and Fischenich 2000). Specific discussion of the role of buffers in flood storage, run-off reduction, and bank stabilization is provided below.

i. Providing flood storage capacity

Buffers promote floodplain water storage and minimize downstream flooding potential in a variety of ways. They intercept overland flow and increase water retention time, which result in reduced flood peaks (Fischer and Fischenich 2000). They also regulate stream flow and facilitate infiltration of surface water, which lead to less severe water level fluctuations during storm events (Bennett 2010, Chase et al. 1995). This regulation of water level fluctuation is important since sudden, high magnitude fluctuations often destroy wetland vegetation, particularly along the wetland edge. This loss of native wetland vegetation can then lead to an increased abundance of invasive plant species and alteration of invertebrate communities (Castelle et al. 1992). The minimum buffer width recommended for effective flood storage was 66 feet (Fischer and Fischenich 2000), with recommendations of minimum widths up to 492 feet (Fischer and Fischenich 2000) or 25 feet beyond the extent of the 100-year floodplain (Bennett 2010).

ii. <u>Reducing run-off and stabilizing the channel bank</u>

Vegetation within buffer areas stabilizes riparian shorelines through complex root systems that are often able to withstand cyclic flooding, ice scour, and natural erosion (Chase et al. 1995). The role of root systems in stabilizing shorelines depends on the plant taxa: herbaceous plants with fibrous root systems protect banks from surface erosion, and woody species with deeper roots increase soil cohesion and reduce mass slope failure (Bentrup 2008). Buffers also impede the flow of water runoff by allowing it to percolate into the ground, which preserves soil composition in periods of intense rainfall (Castelle et al. 1992). Likewise, foliage and branches reduce wind energy by physically interrupting flow paths (Bentrup 2008). In fact, a vegetative windbreak protects a downwind area that is ten to 15 times the height of the trees – a service that reduces soil erosion and stabilizes the soil (Bentrup 2008). The minimum buffer width reported for effective bank stability and run-off reduction was 164 feet (Environmental Law Institute 2008).

iii. <u>Infiltrating surface water</u>

Infiltration is defined as the process by which surface water enters the soil. While we were unable to find specific buffer width recommendations for infiltration in the literature, it is important to recognize the benefit that buffers provide by infiltrating surface water. Infiltration allows pollutants and sediment to be intercepted and removed from the water column before reaching the water body (Sweeney and Newbold 2014). Infiltration also reduces the severity of flood events, as mentioned previously. Coarser-textured soils, such as sandy soils, typically have higher infiltration than finer-textured soils (Bentrup 2008).

III. Habitat for Biodiversity

Buffers provide vital habitat for a diversity of aquatic, semi-aquatic, and terrestrial fauna. Specifically, buffers serve as important sites for foraging, hibernation, breeding, nesting, connectivity and escape from flooding (Groffman et al. 1991, Naiman et al. 1993). Buffers also provide visual separation between wetlands and developed environments, thereby reducing noise and light pollution to sensitive wildlife (Castelle et al. 1992). Nearly 80 vertebrates (bird, mammal, reptile and amphibian) species in the northeastern US have a strong preference for riparian habitats (DeGraaf and Yamasaki 2000). Similarly, of the ~450 species of reptiles, amphibians, mammals, and birds that occur in New Hampshire, ~90 depend on wetlands during some phase of their breeding cycle, and 50 more use wetlands for breeding or foraging habitat (Chase et al. 1995). This amounts to about one-third of New Hampshire's native wildlife depending on aquatic and wetland habitat. There are also a host of rare plants and natural communities associated with riparian areas.

It is important to note that while many species prefer buffers compared to terrestrial habitat farther from the wetland edge, this does not necessarily mean that maintaining buffers alone is sufficient to ensure their needs are met. A seminal meta-analysis undertaken by Marczak et al. (2010) assessed whether forested riparian buffers maintained riparian fauna at densities close to those found in unharvested forest. They found that whether forested buffers alone were sufficient to maintain largely unaltered patterns of abundance depended on the taxa: Amphibians were less abundant in forested buffers compared with control sites in unharvested forest. Small mammals demonstrated a marginally decreased abundance in buffers compared with control sites. Birds were slightly more abundant, however, the species composition of avifauna switched to more edge-associated species. Arthropods were the only taxa assessed in which an increase in abundance was found in buffers compared to control sites. Furthermore, the review found no relationship between buffer width and the magnitude of difference (effect size) between buffers and control sites. This review clearly demonstrates that the maintenance of buffers alone is likely to be insufficient if the management goal is to retain areas of natural habitat with the same suitability found in unaltered terrestrial landscapes. While buffers do support a host of wildlife species, they do not do so to the extent that unaltered terrestrial landscapes do.

While the meta-analysis undertaken by Marczak et al. (2010) did not find a significant relationship between buffer width and the quality of riparian habitat, variation in the known ecology of individual species and taxa provides compelling evidence that minimum buffer widths will vary among different organisms. For example, wood frogs (*Lithobates sylvaticus*) range considerably farther from the wetland edge compared to spotted salamanders (*Ambystoma maculatum*), thus the area of buffer needed to ensure most of the population is distributed within suitable forested habitat varies between the two species (Harper et al. 2015). Since the buffer widths required for wildlife habitat are generally larger than those required for other buffer functions, ensuring wildlife protection when determining buffer widths will in turn protect the other various buffer functions. Generally, the wider the buffer width, the greater the habitat diversity, which can support a greater number of wildlife species (Chase et al. 1995). The majority of published studies have recommended a minimum width of 328 feet for wildlife in general, i.e. considerably wider than recommendations for most other buffer functions (Appendix 3). Discussion of specific recommendations for individual taxa is provided below.

i. <u>Aquatic macroinvertebrates and fish</u>

Aquatic macroinvertebrates and fish are known to be sensitive to changes in habitat structure and function, hence their common usage as indices of biotic integrity (Lammert and Allan 1999, Herlihy et al. 2005). Buffers can play an important role in determining this habitat structure by maintaining inputs of organic material as a basis for aquatic food webs, providing woody debris and hence habitat heterogeneity in the stream, maintaining water quality, reducing inputs of terrestrial sediments, and supporting lower water temperatures and higher concentrations of dissolved oxygen through shading

(Jones et al. 2006). The maintenance of buffers is clearly of greater importance for those species and taxa that are particularly sensitive to alteration of natural conditions in the aquatic environment. Examples of these include cold-water associated species such as brook trout (*Salvelinus fontinalis*) and other salmonids where suitable spawning habitat can be degraded by increased sedimentation leading to lower reproductive success (Scrivener and Brownlee 1989). The majority of published studies have recommended a 98-foot buffer for adequate fish and aquatic macroinvertebrate habitat (Appendix 3), although recommendations of over 300 feet have been suggested for the latter taxa (Environmental Law Institute 2003).

ii. <u>Amphibians</u>

Terrestrial habitat adjacent to wetlands is widely recognized as critical habitat for many amphibian species (Semlitsch 1998). Juvenile and adult amphibians such as mole salamanders (*Ambystoma sp.*), wood frogs (*Lithobates sylvaticus*), and American toad (*Anaxyrus americanus*) spend much of their time in upland habitat. As the majority of animals tend to remain close to suitable wetland breeding habitat (Rittenhouse and Semlitsch 2007) and many species of amphibians in the northeastern US are considered forest-associated (Gibbs 1998), maintaining naturally vegetated buffers is considered critical to local population persistence (Harper et al. 2008). As amphibians differ in vagility, estimates of the extent of terrestrial buffer needed to ensure population persistence vary among species. A meta-analysis undertaken by Harper et al. (2008) estimated that buffers would need to be 3,281 feet wide to encompass 100 percent of the wood frogs in a population and 951 feet wide for spotted salamanders. The review undertaken by NHANRS reported a mean recommended minimum buffer width of 256 feet (Appendix 3). In addition to providing critical habitat for local populations of amphibians, wetland buffers may also help to foster connectivity within metapopulations (Baldwin et al. 2006). Recent work has highlighted the importance of this inter-population movement in maintaining the persistence of regional populations of amphibian species (Harper et al. 2015).

iii. <u>Reptiles</u>

Similarly to amphibians, many species of reptiles are reliant on suitable aquatic and terrestrial habitat in order to complete their life history cycles (Bennett 2010, Semlitsch and Bodie 2003). Species such as common snapping (*Chelydra serpentina*) and painted (*Chrysemys picta*) turtles spend the majority of their time in wetlands and rivers, emerging onto land to lay eggs or to move in search of more suitable habitat (Gibbs et al. 2007). Other species such as Blanding's (*Emydoidea blandingii*), wood (*Glyptemys insculpta*), and spotted turtles (*Clemmys guttata*) roam more widely in the terrestrial environment, often accessing a number of different wetlands throughout the year (Arvisais et al. 2004, Joyal et al. 2001, Refsnider and Linck 2012). Maintaining buffers for these organisms is particularly important as their reliance on wetlands and uplands means that individuals are often concentrated immediately adjacent to the wetland edge. If habitat alteration (particularly road development) occurs along this wetland interface, significant mortality can occur, leading to reduced abundances and population viability (Gibbs and Shriver 2002, Aresco 2005). For wide-ranging species, riparian buffers may also form important movement corridors, thereby increasing the probability of persistence of both local and regional populations (Arvisais et al. 2002, Shoemaker and Gibbs 2013). Estimates of the minimum buffer widths needed to maintain adequate reptile habitat ranged considerably from 100 feet (Bentrup 2008) to more than 3,000 feet (Kiviat 1997), with a median minimum of 417 feet (Appendix 3).

iv. <u>Birds</u>

Many species of birds demonstrate a preference for habitat on the wetland/upland interface for nesting, foraging, and movement among adjacent areas (Bennett 2010, Naiman and Decamps 1997). In fact, avian density and species richness in riparian areas have been estimated to be nearly double the amounts in upland areas (Medina et al. 2016). Maintaining buffers in otherwise altered landscapes can conserve the preferred riparian habitat (Machtans et al. 2002), although the extent to which the needs of birds are met is dependent on both the characteristics of the buffer (habitat type, width, and landscape context) and the requirements of individual species (Saab 1999, Shirley 2004, Smith et al. 2008a). For example, buffers are often occupied by more ubiquitous edge species rather than those typically found in the forest interior (Whitaker and Montevecchi 1999, Pearson and Manuwal 2001, Marczak et al. 2010), with buffers of more than 147 feet needed to conserve the latter taxa (Pearson and Manuwal 2001, Shirley and Smith 2005, Shirley 2006). Given variation in the needs and sensitivity of different bird taxa to habitat alteration, recommended minimum buffer widths also vary: the mean minimum buffer width for adequate waterfowl habitat was 108 feet (Appendix 3), whereas the minimum width for adequate passerine bird habitat was 200 feet (Boyd 2001; Bentrup 2008), and the majority of sources have recommended a minimum width of 328 feet for adequate bird habitat overall (Appendix 3).

v. <u>Mammals</u>

Mammals in New Hampshire vary in their preference for buffer habitat. Species such as river otter (*Lutra canadensis*), mink (*Neovison vison*), beaver (*Castor canadensis*), and American water shrew (*Sorex palustris*) are wetland obligates that use buffers as critical habitat for feeding, cover, denning, and travel ways. Species such as moose (*Alces alces*) are also closely associated with wetlands and the wetland/upland interface during summer months when they use these areas for browsing, escape from insects and predation, and thermoregulation (Koitzsch 2002). Similarly, southern bog lemming (*Synaptomys cooperi*) and snowshoe hare (*Lepus americanus*) are often found at higher abundances in upland habitat adjacent to wetlands, likely as a result of the availability of browse and escape cover (D. Patrick, unpub. data).

In addition to the need to conserve buffer habitat for mammalian species reliant upon this resource, maintaining buffers in otherwise altered landscapes can also support the continued persistence of species distributed more widely across upland habitat (Cockle and RIchardson 2003, Marczak et al. 2010). For example, research in agricultural landscapes in southern Quebec reported 14 species of small mammals in remnant riparian buffer strips (Maisonneuve and Rioux 2001). The value of buffers in altered landscapes for maintaining regional connectivity has been a topic of considerable debate, however there is compelling evidence to indicate that retaining or restoring connectivity among otherwise isolated patches of suitable habitat is likely to increase the likelihood of population persistence (Beier and Noss 2008).

Despite the likely importance of buffers for mammalian species, relatively little research has focused explicitly on determining minimum buffer widths (Wenger 1999). Similarly to other taxa, this minimum is heavily influenced by the needs of the species, habitat structure within the buffer, and the surrounding landscape context. Bearing this in mind, a minimum recommended buffer width for adequate mammal habitat of 100 feet has been proposed (Bentrup 2008) with the mean minimum buffer width recommended of 245 feet in the published literature (Appendix 3).

Table 2. Benefits conveyed by buffers.

Buffer Function	Benefit	Attributes of Buffer
Water Quality	Reducing inputs of excess nutrients and contaminants	Highly dependent on soil type, vegetation type, topography, hydrology
	Mediating sediment	Assumes vegetated buffer
	Influencing water temperature	Assumes buffer with tall vegetation adjacent/over water body, typically forested
	Providing organic inputs into aquatic systems	Assumes vegetated buffer
Hydrologic Effects	Providing flood storage capacity	Assumes vegetated buffer
	Reducing run-off and stabilizing the channel bank	Typically assumes forested buffer
	Infiltrating surface water	--
Habitat for Biodiversity	Aquatic macroinvertebrates and fish	Buffer habitat must meet species' needs
	Amphibians	
	Reptiles	
	Birds	
	Mammals	

Table 3. Summary of minimum recommended buffer widths by overall buffer function from the literature.

Buffer Function	Minimum Width Recommended by Study Authors	Median Width Recommended by Study Authors	Maximum Width Recommended by Study Authors
Water Quality	16 feet	100 feet	400 feet
Hydrologic Effects	33 feet	98 feet	330 feet
Habitat for Biodiversity	50 feet	328 feet	1,969 feet

Table 4. Summary of minimum recommended buffer widths by ecosystem service provided by each buffer function from the literature.

Buffer Function	Benefit	Recommended Buffer Width
Water Quality	Reducing inputs of excess nutrients and contaminants	98 feet
	Mediating sediment	98 feet
	Influencing water temperature	30 feet
	Providing organic inputs into aquatic systems	50 feet
Hydrologic Effects	Providing flood storage capacity	66 feet
	Reducing run-off and stabilizing the channel bank	164 feet
	Infiltrating surface water	None found
Habitat for Biodiversity	Aquatic macroinvertebrates and fish	98 feet
	Amphibians	256 feet
	Reptiles	417 feet
	Birds	328 feet
	Mammals	245 feet

E. What previous and ongoing attempts have been made to address ecological stressors and maintain ecosystem services using buffers, and what technical barriers have been encountered?

Given the likely efficacy of buffers in reducing ecological stressors and maintaining ecosystem services, it is not surprising that a number of watersheds in the United States have attempted widespread implementation of buffer conservation and restoration. While the intensity of these efforts and the context within which they have occurred varies considerably, important lessons can be learned from reviewing the following case studies. These have been chosen based on their description of the implementation strategy (quantification of approaches or methods used), relevance of watershed scale (similar to the scale at Great Bay), inclusion of a quantification of outcomes (tangible results for lessons learned from the implementation), and similar ecological/social/cultural/regulatory context to the Great Bay watershed. Primarily, these studies were conducted in North America. Presentation of these case studies is organized by relevant "frequently asked questions."

I. What successes have arisen from buffer restoration and protection attempts?

The following case studies represent examples of buffer restorations that have been "successfully" employed, i.e., natural vegetation has been re-established. Where information is available, we have also discussed the evidence that these restoration efforts have resulted in quantifiable benefits to target ecosystem services. Also included are case studies highlighting successful protection efforts that have maintained functional buffers in places where they still occur. Compared to restoration, fewer case studies have quantified the ecosystem service benefits of protection of existing buffers. More specifically, we were unable to find watershed-scale case studies that had compared the benefits of using available resources to conserve existing buffers versus restoring lost buffers. We flag this as a research gap given that restoration is often costly and not always successful.

i. North Hampton, New Hampshire

Various water quality and habitat improvement projects throughout the Northeast have specifically implemented buffer restoration and protection as their keys to success in meeting their objectives. As a local example, riparian buffers have been restored at the Sagamore-Hampton Golf Course in North Hampton, New Hampshire through the New Hampshire Sea Grant's Coastal Research Volunteers program (Fig. 5). More than 100 trees and shrubs were planted in early summer 2016, including river birch (*Betula nigra*), sweet pepper bush (*Clethra alnifolia*), and fragrant sumac (*Rhus aromatic*, Gro-lo cultivar). As of August 2016, survival was 100 percent, despite the drought (A. Eberhardt, pers. comm.).

Figure 5. Pre- and post-restoration photos of a riparian buffer area in North Hampton, New Hampshire. Photos provided by New Hampshire Sea Grant.

ii. **Connecticut River Watershed**

Floodplain restoration along the Connecticut River is another example of a project that has successfully implemented buffer restoration and protection in the Northeast. Since 2009, The Nature Conservancy and partners have spearheaded an effort to protect and restore floodplain forest within the Connecticut River watershed. This initiative began with prioritization of tracts for protection and restoration based on criteria including the existence of low, regularly flooded terraces and extensive shoreline, the potential of the tract to serve as a linkage to protected areas across the river, and location of the tract in an active river area of the Connecticut. Within these priority areas, the Conservancy and its partners have implemented an adaptive management approach to restoration that will help determine the most cost effective approach to bring back silver maple (*Acer saccharinum*), American elm (*Ulmus americana*), and other native floodplain species on floodplain terraces that have a hydrologic regime to support this habitat into the future. These efforts have led to an increased understanding of the most appropriate management techniques for successful restoration (Marks 2013), as well as forested riparian buffer restoration on a number of properties, including the 252-acre Potter Farm tract in New Hampshire.

iii. **Chesapeake Bay Watershed**

A third example of a successful, targeted buffer restoration project is within the Chesapeake Bay watershed. Forested buffers have been planted within the watershed since 1996, covering more than 8,152 miles (Chesapeake Bay Program 2013). The initiative has been undertaken through the implementation of riparian forest buffer incentive programs, most notably the Conservation Reserve Enhancement Program (CREP). In the most productive years, the bay states averaged 830 miles of buffers alongside riparian areas restored per year. Proper use of tree tubing and herbicide application were found to greatly improve restoration success (Chesapeake Bay Program 2013).

iv. Columbia River Watershed

In other areas of the United States, buffer restoration projects have had success in targeting areas impacted by forestry and agriculture. In the Columbia River watershed in the western United States, since the 1960's buffer areas have been added to reduce the impacts of logging – in particular, slope failure and soil erosion (National Research Council 2004). Additionally, Washington State's Conservation Reserve Enhancement Program (CREP) has provided financial incentives for farmers to restore riparian buffers on agricultural land for nearly 20 years. Survival of planted vegetation ranged from 75 percent to 90 percent throughout the state, with most positive results seen after 5+ years of the buffer being implemented, especially for canopy cover, which provides the service of shading the buffer and adjacent water body (Smith 2012).

v. Fox Creek Canyon, Oregon

In Oregon in 2003, the Fox Creek Canyon underwent a restoration project coordinated by various partnering agencies to mitigate the degradation caused by open-range cattle grazing. Sixteen acres were seeded with native grasses, 4,000 native cuttings and seedlings were planted, and 7 miles of fence were installed to exclude cattle (Machtinger 2007). Results were not quantified, but grasses and forbs had regenerated on the banks of Fox Creek within two years of the restoration efforts.

vi. Bog Brook, New Hampshire

Various other projects in the Northeast and western United States that included buffer restoration as a component of their water quality and habitat improvement techniques demonstrated successes, although the degree to which buffer restoration contributed to the successes remains indeterminable. A buffer was implemented as part of a streambank stabilization project at Bog Brook in the upper Connecticut River basin of northern New Hampshire, an area dominated by agriculture. Riparian vegetation was removed decades ago, presumably to increase the arable land area available, which caused streambank erosion and a subsequent decline in water quality (U.S. Environmental Protection Agency 2006). In 2004, the streambank was stabilized through natural stream channel design, including planting of deep-rooted shrubs to form a vegetated buffer to supplement the shallow-rooted (six-inch) grasses in existence. The shrubs consisted of alder and willow, among others. One-year post-construction, the vegetation was well-established and firmly rooted, and the channel had become more narrow and deeper, both indicative of channel stability. Because of this restoration, Bog Brook was reclassified as "Fully Supporting" from "Impaired" by the New Hampshire Department of Environmental Services.

vii. Mousam Lake, Maine

Another project that included buffer implementation to address water quality issues was the restoration of Mousam Lake's shoreline in southern Maine. The lake's water quality had been in decline for decades due to excessive phosphorus inputs via stormwater runoff. However, after ten years of nonpoint source pollution control projects that started in 1997, water clarity increased by three feet, the lake was in a stable or improving trophic state, and it attained water quality standards set by the Maine Department of Environmental Protection, thereby allowing it to be removed from the list of impaired water bodies (U.S. Environmental Protection Agency 2008). Best management practices, including vegetated buffer plantings, were installed along the lake shoreline at 45 priority sites to stabilize erosion and improve roadside drainage and gravel road surfaces. The associated reduction in pollutant loading to the lake was more than 150 tons of sediment and 130 pounds of phosphorus per year – this equates to a ten percent reduction in phosphorus to the lake. Consequently, this high profile work inspired protection efforts on several neighboring lakes.

viii. Highland Lake, Maine

Similarly, buffer restoration was one method used to combat water quality declines in Highland Lake outside of Portland, Maine. In the 1980's and 1990's, the lake showed signs of declining water quality caused by excessive soil erosion throughout the watershed. Restoration work beginning in 1997 addressed significant erosion sites and reduced polluted runoff by planting more than 1,000 shrubs, trees, and groundcovers, and installing other best management practices such as water bars, rain gardens, and riprap. Lake water clarity stabilized and met water quality standards, thereby allowing it to be removed from the state's list of impaired water bodies in 2010. Furthermore, the amount of sediment and phosphorus exported to the lake declined significantly; it was estimated that pollutant loading was reduced by 278 tons of sediment and 1,070 pounds of phosphorus per year (U.S. Environmental Protection Agency 2010).

ix. Gila River Watershed

Although not topographically similar to the Northeast, the Gila River watershed provides another example of buffer restoration and protection being used to revive an impaired watershed successfully. Portions of the watershed within Arizona and New Mexico have been degraded by past fire management, logging, and domestic grazing practices, thereby reducing water quality, species diversity, and floodplain function (Natural Resources Conservation Service 2006). Protection and restoration efforts began in the late 1970's and included prescribed fire, improved livestock and off-road vehicle management, and the use of bioengineering techniques. Protection and restoration of the riparian area appears successful, as a new rare species of stonefly was observed during biotic condition index monitoring, breeding numbers of the southwestern willow flycatcher increased, and sediments and ash were observed to be trapped onsite rather than lost downstream.

II. What obstacles have been encountered in buffer restoration and protection attempts?

While numerous buffer restoration and protection projects have been successful, others have faced challenges in their implementation strategies. The following case studies serve as examples of efforts that involved roadblocks, both on-the-ground and conceptually. We also highlight certain obstacles faced by a land trust in its attempt to protect buffers through regulatory framework.

i. Chesapeake Bay Watershed

The Chesapeake Bay watershed's buffer restoration initiative has suffered various setbacks in its watershed-scale attempt to improve the bay's water quality. Based on the number of miles planted, restoration efforts have decreased notably since 2009, likely as a result of declining interest, lack of noticeable effect on water quality and habitat improvement, scarcity of funding, and increased challenge (i.e. most accessible or easiest areas have already been planted). This is despite the fact that forest buffers are one of the most cost-effective methods of improving water quality in the bay. Early plantings suffered from lack of proper site preparation and maintenance (e.g. competing vegetation, lawn mowing, deer browse), which caused planting failure and discouraged stakeholders going forward. Another obstacle was that the CREP program has not been open for enrollment for various periods throughout the restoration effort, and these interruptions in program delivery increased skepticism about program viability. Furthermore, as enrollments in the CREP program expire, it may take up to three years to secure re-enrollment; the amount of effort and financial investment put into initially securing these contracts could easily be canceled out by landowners not re-enrolling (Chesapeake Bay Program 2013).

ii. Connecticut River Watershed

Similarly, the Connecticut River floodplain restoration project in New Hampshire has elucidated some policy-based tensions and on-the-ground hurdles. While a number of buffer protection and restoration projects are underway, the path to reaching a scale at which these efforts translate into large-scale restoration of floodplain forest within the watershed is not yet clear. One particular challenge comes from the fact that productive agricultural lands tend to be concentrated in floodplain lands, particularly in New Hampshire, where only seven percent of the state is considered to be well-suited for agriculture. Thus there is a tension between restoring buffers and maintaining active farming. Furthermore, competition caused by invasive plant species such as oriental bittersweet (*Celastrus orbiculatus*) can lead to high mortality of planted seedlings, particularly in the lower portion of the watershed.

iii. Maidstone, Vermont

As an example of a specific project in the Connecticut River floodplain that has faced hurdles on-the-ground, buffer restoration conducted on one of The Nature Conservancy's preserves in Maidstone, Vermont faced various challenges post-restoration (Fig. 6). The Conservancy partnered with the local Natural Resources Conservation District to install a 100-foot buffer along three sections of eroding riverbank in different years, but the banks have continued to erode and have cut into the restored areas. Additionally, plantings have struggled to survive due to grass competition, lack of water upon installation, and deer herbivory. Wherever possible, the partners have since attempted to plant further back from the bank and to plant widths greater than 100 feet to allow for some bank erosion in this naturally meandering section of river. One year after planting, mesh tubing was installed to protect against deer herbivory. The Nature Conservancy employs an adaptive management approach for all buffer restoration projects in the Connecticut River watershed, thereby allowing flexibility in post-restoration management approaches depending on the outcomes observed following the restoration work. Through the adaptive management strategy, the lessons learned from restoration challenges can be employed in subsequent restorations, thereby facilitating more effective approaches in the future.

Figure 6. Before (left) and after (center, right) photos of buffer restoration from The Nature Conservancy's Maidstone Bends Preserve along the Connecticut River in Maidstone, VT. Photos provided by The Nature Conservancy in Vermont.

A review of six national case studies focused on riparian buffer projects highlighted the top challenges that the projects faced throughout the United States. The greatest obstacle identified was securing funding (Frey 2013). Invasive species and survival of planted trees also ranked highly as common issues encountered. Another stumbling block was the difficulty of working with private landowners, which encompassed coordination of multiple sites, willingness of property owners to consider buffer implementation, and concern about "giving up" land to buffers. Other issues that arose during implementation projects included weather events that affected the survival of plantings (e.g. severe wind storms, landslides) (Bisson et al. 2013) and lack of long-term monitoring for plantings to determine persistence of efficacy (Smith 2012).

Lastly, there are various obstacles to enacting regulatory buffer protections, which the Pennsylvania Land Trust Association (2014) outlined. For instance, landowners and other community members may not appreciate the value of buffers or the areas that they protect. People who have a financial interest in development or those who are ideologically opposed to development restrictions may push back against proposed regulatory protections. Likewise, some may want to exempt certain agricultural or forestry practices from restriction. Lastly, finding agreement on an adequate buffer width that is both ecologically sound and politically acceptable may be difficult (Pennsylvania Land Trust Association 2014).

III. What are the overarching lessons learned from buffer restoration and protection attempts?

A number of overarching lessons can be drawn from our case study review. While appropriate methods for successfully restoring buffers are now well-understood, factors such as invasive species and browsing herbivores can still lead to challenges. Additionally, there has been success in restoring buffers at scale in some places, but in other areas, the path to large-scale restoration is not clear, and maintaining the energy required to propel restoration efforts over time is difficult. Furthermore, there is some concern that restoration may take precedence over conservation of buffers. This may be true, given that natural buffers have already largely been lost throughout the Northeast, but it is important to recognize the value of proactively maintaining what we already have, rather than reacting to restore what has been lost.

Programs that have implemented restoration projects also provide important "lessons learned" for future efforts. One major theme is the need to secure adequate funding, including resources to support landowner outreach and maintenance of established buffers by encouraging enrollment as well as re-enrollment in restoration programs (Chesapeake Bay Program 2015). Conservation Reserve Enhancement Program (CREP) and Environmental Quality Improvement Program (EQIP) funding should be utilized to their fullest extents – there is no established funding limit for CREP, and most states are well under their CREP acreage caps (Chesapeake Bay Program 2013).

Another important lesson regarding buffer restoration is the need to employ an adaptive management approach. Using this approach, each restoration is considered an experiment, and monitoring is conducted post-restoration to determine how and where certain restoration approaches are effective. This monitoring is vital, given that there will inherently be spatial and temporal variability among each restoration project that may affect its outcome relative to other projects. Employing adaptive management enables managers to implement improved and tailored restoration methods going forward.

A further lesson learned for buffer protection and restoration was the importance of sufficient preparatory work and conservation planning. For example, programs could conduct localized geographic analyses to strategically target specific locations where buffers would be most beneficial in nutrient load reduction, as this is a cost-effective approach that accounts for the fact that water quality contributions vary at a local scale depending on adjacent land use and other factors (e.g. the amount and direction of subsurface flows) (Chesapeake Bay Program 2013). Datasets are being developed that illustrate concentrated flow paths over high-resolution land use data to prioritize areas for targeted restoration where pollutant and nutrient runoff has the greatest effect on the water body (Allenby and Phelan 2013), and to prioritize areas for targeted protection where there are high-functioning natural landscapes (Allenby and Burke 2012). As an additional planning tool, it is important to recognize that planted buffers may still be susceptible to erosion, especially on steep slopes; engineered structures prepared from large woody debris or geotextile mats and rolls can effectively support planted vegetation (Medina et al. 2016). Furthermore, post-restoration monitoring and adaptive management should be implemented to assess success and control for invasives (Medina et al. 2016). Additionally, programs could consider buffer protection in addition to restoration. Protection is considered by some organizations an easier, more successful, and cost-effective method. To capitalize on previous restoration efforts, buffer protection could be targeted to areas where restoration has been undertaken through public funding. Lastly, a targeted conservation framework should be implemented in state and local laws and ordinances to emphasize the protection of buffers (Chesapeake Bay Program 2013).

The case studies highlighted in this review demonstrate that there may be differences in buffer efficacy and function in environmental settings as compared to the experimental settings from which much of the review's width recommendations are sourced. In general, these case studies raise an important cautionary note that buffers do not represent a panacea in terms of mitigating environmental stressors and providing critical ecosystem services. It is also clear that quantitatively linking the maintenance or restoration of buffers to key services such as water quality outside of an experimental arena can be difficult. The latter issue is not surprising given that well-designed studies invariably involve controlling factors other than those of interest, whereas real-world application of buffers occurs within a highly stochastic, multi-variate, and often un-replicated environment (i.e. "the real world"). The challenge in linking the use of buffers to clear environmental benefits in real-world applications is important to recognize, particularly when communicating with relevant stakeholders. However, it is also vital that we highlight the important evidence drawn from controlled studies in which specific cause-and-effect mechanisms linking buffers to the services they provide have been tested and validated.

Appendix 1.

Literature review summary table of buffer widths for water quality. Reproduced with permission from Rick Van de Poll, Chair, NHANRS Wetland Buffer Scientific Work Group. Color coding corresponds as follows: light gray – wetlands, light blue – streams, dark gray – vernal pools, yellow – ponds less than 10 acres, dark blue – ponds greater than 10 acres.

CITATION TYPE	AREA OF CONCERN RELATIVE TO WETLAND/RIPARIAN ZONE FUNCTION INTEGRITY					
Buffer Research Compendia	GENERAL	Sediment	TDS/TSS	Nitrogen	Phosphorus	Organics (e.g. bacteria)
Sweeney & Newbold (2014)	≥ 98 ft.					
Chase, Deming & Latawiec (1995)	≥ 100 ft.					
Sheldon et al. (2005)	≥ 197 ft.	66 – 328 ft.		≥ 66 ft.		
Granger et al. (2005)	40 - 75 ft.					
Wenger (1999)[1]		≥ 98 ft.		≥ 98 ft.	≥ 98 ft.	
Nieber (2011)			≥ 100 ft.	≥ 100 ft.	≥ 100 ft.	
Straughan Environmental Services, Inc. (2003)[2]	82 - 98 ft.					
Sweeney & Newbold (2014)		≥ 98 ft.[3]		≥ 131 ft[4]		
BMP Guides						
Environmental Law Institute (2003)		≥ 82 ft.	≥ 82 ft.	≥ 82 ft.	≥ 82 ft.	
Environmental Law Institute (2008)[5]		30 - 100 ft.		100 - 165 ft.	30 - 100 ft.	30 - 100 ft.
Fischer & Fischenich (2000)	16 - 98 ft.					
deMaynadier et al. (2007)	50 - 330 ft.					
Calhoun & Klemens (2002)	≥ 100 ft.					
deMaynadier et al. (2007)	50 - 400 ft.					
Wenger (1999)[1]		≥ 98 ft.		≥ 98 ft.	≥ 98 ft.	
Fischer & Fischenich (2000)	16 - 98 ft.					
Good Forestry in the Granite State (2010)[3]	≥ 100 ft.					
deMaynadier et al. (2007)	50 - 250 ft.					
deMaynadier et al. (2007)	75 - 125 ft.					
Good Forestry in the Granite State (2010)[3]	100 ft.					
deMaynadier et al. (2007)	100 - 330 ft.					
Good Forestry in the Granite State (2010)[3]	300 ft.					
Journal Articles / Technical Reports						
Murphy & Golet (1998)	≥ 100 ft.					
Schwerr & Clausen (1989)[6]		≥ 98 ft.	≥ 98 ft.	≥ 115 ft.	≥ 115 ft.	
Murphy & Golet (1998)	≥ 100 ft.					
Murphy & Golet (1998)	≥ 150 ft.					
Ahola (1990)	≥ 160 ft.					
Correll & Weller (1989)				≥ 60 ft.		

Peterjohn & Correll (1984)		≥ 60 ft.				
Rhode Island Rivers Council (2005)	≥ 300 ft.					

Additional Information

[1] Wenger also suggests adding 2 ft. for every 1% of slope
[2] Based on 21 papers related to water quality concerns; also recommended 3-zone system: Zone 1: 15 ft. (natural); Zone 2: 60 ft. (managed); Zone 3: 20 ft. (grazed)
[3] Each recommended RMZ suggests a minimum 'no-cut' zone: ponds: 0 ft.; great ponds: 25 ft.; 4th order +: 25 ft.; 3rd order: 50 ft.; 1st & 2nd order: 25 ft.
[4] Median removal rate was 65% for 33 ft. buffer and 85% for 98 ft. buffer for 28 studies of both grass and forest buffer sites
[5] McElfish, Kihlsinger, & Nichols are the principal authors
[6] For removal of > 90% of the pollutant

Appendix 2.

Literature review summary table of buffer widths for hydrologic effects. Reproduced with permission from Rick Van de Poll, Chair, NHANRS Wetland Buffer Scientific Work Group. Color coding corresponds as follows: light gray – wetlands, light blue – streams, dark gray – vernal pools, yellow – ponds less than 10 acres, dark blue – ponds greater than 10 acres.

CITATION TYPE	AREA OF CONCERN RELATIVE TO WETLAND/RIPARIAN ZONE FUNCTION INTEGRITY		
Buffer Research Compendia	GENERAL	Run-Off/Bank Stability	Flood Storage
Granger et al. (2005)	50 - 110 ft.		
Wenger (1999)[1]	33 - 98 ft.		
Straughan Environmental Services, Inc. (2003)[2]	82 - 98 ft.		
Sweeney & Newbold (2014)	≥ 82 ft[3]		
Murphy (N.D.)	100 ft.		
Vermont Agency of Natural Resources (2005)	37 - 225 ft.		
Bolton & Shellberg (2001)[4]			100-yr floodplain
BMP Guides			
Environmental Law Institute (2003)	≥ 98 ft.	≥ 164 ft.	
deMaynadier et al. (2007)	50 - 330 ft.		
Calhoun & Klemens (2002)	≥ 100 ft.		
Wenger (1999)[1]	33 - 98 ft.		
Fischer & Fischenich (2000)	33 - 66 ft.		66 - 492 ft.
Good Forestry in the Granite State (2010)[5]	100 ft.		100-yr flood-plain + 25 ft.
deMaynadier et al. (2007)	50 - 250 ft.		
deMaynadier et al. (2007)	75 - 125 ft.		
Good Forestry in the Granite State (2010)[5]	100 ft.		
deMaynadier et al. (2007)	100 - 330 ft.		
Good Forestry in the Granite State (2010)[5]	300 ft.		
Journal Articles / Technical Reports			
Murphy & Golet (1998)	≥ 100 ft.		
Murphy & Golet (1998)	≥ 150 ft.		
Rhode Island Rivers Council (2005)	≥ 300 ft.		
Additional Information			

[1] Wenger also suggests adding 2 ft. for every 1% of slope
[2] Based on 21 papers related to water quality concerns; also recommended 3-zone system: Zone 1: 15 ft. (natural); Zone 2: 60 ft. (managed); Zone 3: 20 ft. (grazed)

[3] Based on 38 studies in a variety of locales and with variable cover types; median removal rate for this distance was 89%

[4] Applicable for 55% of species; 5 spp. < 100 ft.; 3 spp. 100 - 200 ft.; 9 spp. > 200 ft.

[5] Each recommended RMZ suggests a minimum 'no-cut' zone: ponds: 0 ft.; great ponds: 25 ft.; 4th order +: 25 ft.; 3rd order: 50 ft.; 1st & 2nd order: 25 ft.

Appendix 3.

Literature review summary table of buffer widths for habitat for biodiversity. Reproduced with permission from Rick Van de Poll, Chair, NHANRS Wetland Buffer Scientific Work Group. Color coding corresponds as follows: light gray – wetlands, light blue – streams, dark gray – vernal pools.

CITATION TYPE	**AREA OF CONCERN RELATIVE TO WETLAND/RIPARIAN ZONE FUNCTION INTEGRITY**							
Buffer Research Compendia	GENERAL	Aquatic Macro-Invertebrate	Amphibian	Reptile	Fish	Waterfowl	Passerine Bird	Mammal
Chase, Deming & Latawiec (1995)	100 - 300 ft.							
Boyd (2001)[1]			≥ 200 ft[2]	≥ 200 ft[3]		≥ 200 ft[4]	< 200 ft[4]	≥ 200 ft[5]
Desbonnet et al. (1994)	246 - 1,969 ft.							
Sheldon et al. (2005)			384 - 673 ft.				≥ 328 ft.	≥ 328 ft.
Granger et al. (2005)		≥ 100 ft.	390 - 1900 ft.	440 – 3,700 ft.	≥ 100 ft.		390 – 2,000 ft.	250 - 650 ft.
Wenger (1999)[6]	≥ 328 ft.							
Nieber (2011)	500 - 950 ft.							
Sweeney & Newbold (2014)	≥ 98 ft. [7]		≥ 98 ft.					
Murphy (N.D.)		100 ft.			100 ft.			
Vermont Agency of Natural Resources (2005)	10 - 840 ft.							
Lichtin (2008)	50 - 200 ft.							
Bolton & Shellberg (2001)[4]	150 - 250 ft.							
BMP Guides								
Bentrup (2008)		100 - 200 ft.	100 - 600 ft.	100 - 600 ft.		100 - 330 ft.	200 ft. - 5,280 ft.	100 - 330 ft.
Environmental Law Institute (2003)	≥ 328 ft.	≥ 328 ft.						
Environmental Law Institute (2008)[8]	100 - 950 ft.							
Calhoun & Klemens (2002)	100 - 750 ft.							
Bentrup (2008)		100 - 200 ft.	100 - 600 ft.	100 - 600 ft.				
U.S. Army Corps of Engineers (2015)	100 - 750 ft.							
Wenger (1999)[6]	≥ 328 ft.							
Fischer & Fischenich (2000)	98 - 1,640 ft.							
Good Forestry in the Granite State (2010)[9]	≥ 300 ft.				≥ 150 ft.			

Journal Articles / Technical Reports								
Groffman et al. (1991)	≥ 328 ft.						≥ 328 ft.	
Kiviat (1997)				3,281 ft[10]				
Semlitsch & Bodie (2003)			522 - 951 ft.	417 - 948 ft.				
Harper et al. (2008)	328 - 541 ft.		328 - 541 ft.					
Rabeni (1991)			25 - 200 ft.		25 - 200 ft.	25 - 200 ft.		
Brown et al. (1990)	300 - 600 ft.							

Additional Information

[1] Based on 9 reptiles, 19 amphibians, 14 mammals, and 23 birds that were identified as "wetland dependent"
[2] Applicable for 58% of species; 1 species 100-200 ft.; seven species < 100 ft.
[3] Applicable for 67% of species; 1 species < 100 ft.; 2 species < 35 ft.
[4] Applicable for 55% of species; 5 spp. < 100 ft.; 3 spp. 100 - 200 ft.; 9 spp. > 200 ft.
[5] Applicable for 80% of species; 2 species found to be within 100 ft.
[6] Wenger also suggests adding 2 ft. for every 1% of slope
[7] For the maintenance of stream bank and stream channel width integrity
[8] McElfish, Kihlsinger, & Nichols are the principal authors
[9] Each recommended RMZ suggests a minimum 'no-cut' zone: ponds: 0 ft.; great ponds: 25 ft.; 4th order +: 25 ft.; 3rd order: 50 ft.; 1st & 2nd order: 25 ft.
[10] Applicable only to Blanding's turtles

Appendix 4.

Summary of knowledge gaps and research needs identified through the compilation of this literature review.

- A literature review examining the extent to which human activity has degraded water resources post-colonization, and what quantity of these resources are needed to retain functioning ecosystem services in a sustainable manner for both humans and biodiversity.
- Research that illustrates the effects of having no buffer on a water body, and the associated percent of nutrient and contaminant inputs that enter the water body.
- Calculable functional relationships between buffer width and amount of pollutant reduction.[1]
- Controlled studies to determine how various buffer characteristics (e.g. vegetative composition, stem density, canopy cover) affect buffer function.
- Robust models estimating flood storage capacity based on buffer width and other important attributes, including basin geomorphology and soil type.
- Robust models estimating run-off reduction and effective bank stability based on buffer width and other important attributes, such as slope and soil type.
- Robust models estimating how buffer width affects the amount of surface water infiltrated.

[1]This ability to link buffer restoration or protection to a specific amount of nutrient reduction is a vital step in helping to promote the use of green infrastructure in meeting water quality improvements. Despite the research need, the University of New Hampshire's Stormwater Center is making progress on this front through its NHDES Pollutant Tracking and Accounting Pilot Project, which will identify potential tools to enable municipalities to quantitatively assess nonpoint source pollutant load reductions in the GBE.

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