CBP/TRS-330-22

A Systematic Review of Chesapeake Bay Climate Change Impacts and Uncertainty: Watershed Processes, Pollutant Delivery, and BMP Performance

Prepared for:
Chesapeake Bay Program
1750 Forest Drive
Annapolis, MD 21403

Suggested Citation: Hanson, J., E. Bock, B. Asfaw, and Z.M. Easton. 2022. A systematic review of Chesapeake Bay climate change impacts and uncertainty: watershed processes, pollutant delivery and BMP performance. CBP/TRS-330-22. Available at https://bit.ly/BMP-CC-synth

Support Provided by
EPA Grant No. CB96326201
NOAA Grant No. NA20NMF4570310

Acknowledgements:
We want to thank and acknowledge the incredibly helpful and constructive comments from Julie Reichert-Nguyen, our steering committee (Raymond Najjar, Julie Shortridge, Kurt Stephenson, Lisa Wainger) and other reviewers including Lew Linker, David Wood, Alex Gunnerson, and Ken Staver. We are also grateful to Gary Shenk and Denice Wardrop for their valuable input. We also wish to thank members of the various Chesapeake Bay Program Goal Implementation Teams and workgroups that listened, and provided valuable input in response, to the numerous presentations dating back to 2020, particularly the Water Quality Goal Implementation Team, Climate Resiliency Workgroup, Modeling Workgroup, and Urban Stormwater Workgroup.

Cover photo: Chesapeake Bay Program, photo by Will Parson. Lightning seen over a no-till field in Pennsylvania.

Executive Summary

Climate change in the Chesapeake Bay will affect the effort to reach the TMDL, and maintain needed nutrient and sediment reductions. In an effort to determine how baseline nutrient and sediment loads will likely change in response to climate, and the best management practices (BMPs) being used to reduce them will function, a modified systematic review process was undertaken. Using this process we reviewed research literature and studies related to two primary questions: 1. How do climate change and variability affect nutrient/sediment cycling in the watershed?; and 2. How do climate change and variability affect BMP performance?

Climate change impacts nutrient and sediment cycling and export in the Chesapeake Bay region via a number of factors, including expected increases in precipitation volume and intensity, rising temperatures, and increased atmospheric CO_2 concentrations. As described in question one, climate change impacts are predicted over a range of scales with increasing uncertainty as direct impacts propagate through biochemical systems. Such derivative hydrologic impacts of increased precipitation include soil moisture and partitioning of surface and subsurface flow, which incorporate temperature and CO_2 effects on biological processing largely through altered evapotranspiration. These climate factors interact via complex mechanisms to influence the watershed and estuary function. Increased precipitation volume is expected to increase the water budget especially in the form of runoff, streamflow, and freshwater flows to the estuary, but seasonal changes (e.g., increase winter and spring precipitation) increase the variability of these responses. Increases in the water budget mobilize and export greater quantities of nutrients and sediment from the watershed to the estuary. Increased precipitation intensity further exacerbates nutrient and sediment export, and large increases in the intensity of the most intense storms is/has been realized.

Climate factors also alter watershed and estuary nutrient and sediment cycling processes, with higher temperatures increasing the rate of nutrient cycling, and increased precipitation, expressed as wetter soils, shifting stoichiometric ratios (e.g., increased phosphorus mineralization or nitrification). While there was considerable viability among studies, consensus predictions indicate that BMPs will need to be capable of assimilating and treating greater nonpoint source nutrient and sediment loads.

There are dozens of nonpoint BMPs that have been assessed and approved by the Chesapeake Bay Program (CBP) for counting toward numeric nutrient and sediment reduction targets. This review attempted to review the widest range of BMPs based on the modified systematic review, which yielded varying numbers and quality of studies to inform this report's understanding of climate change impacts to BMP performance. The most useful insights were gained from key papers, most often meta-analyses and literature reviews, as well as a small number of studies that model BMP performance under future climate conditions, most often with the Soil & Water Assessment Tool (SWAT).

Ultimately, the literature does not provide a comprehensive understanding of BMP function and performance to explicitly illuminate the role that future climate conditions are likely to play, not even for the BMPs where the most literature was found. However, there is enough information to build conceptual frameworks that may serve as a basis for the CBP or others as new research continues to inform a collective understanding of key watershed processes and other variables that affect BMPs en masse, rather than focusing on specific practices. This report describes a conceptual framework that may serve as this basis, with an understanding that more work and future research will continue to refine and improve it. Key features of the framework include categorizing BMPs based on their primary pollutant reduction mechanisms.

This report identifies and discusses key knowledge gaps identified in the literature. Some of the key knowledge gaps described in this report include:

1. Research to inform the selection, design and siting of cost-effective BMPs that are resilient to anticipated long-term changes in hydroclimatic conditions, including (1) design guidance to increase BMP resilience (e.g., standards for considering the impacts associated with extreme weather and climate into BMP siting and design), (2) improved simulation modeling capabilities for BMPs, (3) targeted research to quantify the impacts of climate change on BMP effectiveness and (4) improved methods to evaluate siting and design considerations.
2. Research to evaluate BMP resilience due to climate change and extreme weather events. Extreme weather, amplified by climate change, will continue to threaten our BMP infrastructure. Information about how BMPs function in a changing climate is a precursor to understanding how they are, or are not, resilient to climate change. To the extent possible research should identify processes, pathways, and mechanisms to improve BMP resilience.
3. Modeling studies that assess the performance of one or more BMPs under future climate conditions do not consider alternative land use or population growth scenarios. This is an understandable knowledge gap given the purpose of the reviewed modeling studies is to understand the effectiveness of one or more BMPs in isolation of other changes. However, population growth and other socioeconomic factors will drive significant changes to the landscape and it is well established that that landscape will be a major factor in watershed loads. While the uncertainty of future growth projections may be quite high in the long term, it may be worthwhile for researchers to consider how they might utilize short-or medium-term growth projections in coordination with BMP modeling to assess impacts to loads and BMP effectiveness.
4. Distinguishing between BMP effectiveness and variability. High effectiveness does not necessarily mean less variable performance, in fact, very effective management practices are often highly variable. Likewise BMP effectiveness and uncertainty should be distinguished, as many highly effective BMPs are also subject to considerable uncertainty under a changing climate. Furthermore, performance certainty and adaptability is largely related to BMP typology. With structural BMPs generally providing more certainty in terms of function under climate change but also subject to structural (and water quality) failure as a result of climate change. Management type BMPs generally prove more adaptable to a changing climate, but are subject to diminished performance as a result of climate change. Understanding BMP performance variability and uncertainty is an area of much needed research.

5. Social science linkages were not sought in our searches and review, but there are significant potential contributions of social science fields particularly with respect to improved implementation and appropriateness of individual (or suites of) BMPs.

These challenges are ripe for groups within the Chesapeake Bay Program structure to address, and in many ways the CBP partnership already facilitates this type of longer-term thinking to encourage convergent research.

Due to this review's focus on BMPs for water quality we do not consider a number of closely related systems or practices. For instance, stormwater BMPs discussed in this report work in conjunction with combined or separate storm sewer systems in developed areas. Future work across sectors or within the developed sector may want to directly consider the interrelated effects between BMPs and established infrastructure (gray infrastructure). Aging infrastructure may be a large focus of state and federal partners, especially over the next decade in light of recent federal legislation. There will be a need to consider expected shifts from climate change when designing and installing gray infrastructure the same way that such updated information is needed to inform design and implementation of nonpoint source BMPs. Effort should be made to ensure that knowledge and assumptions applied to gray infrastructure (water, wastewater, stormwater, roads, etc.) are shared with planners and technical assistance providers in the nonpoint source sector.

Even with the body of research available to support a systematic review, the exogenous drivers and internal processes governing nutrient and sediment transport under climate change are highly complex, and significant uncertainties remain.

Finally, this report offers six recommendations for the CBP to consider as next steps to fill the most urgent and glaring knowledge gaps:

1. <u>Develop mechanisms for publication of aggregated BMP inspection failure data.</u> The CBP should consolidate and publish available inspection data collected and reported by the jurisdictions. As noted in this synthesis and others such as Lintern et al. (2020), the BMP performance literature rarely, if ever, includes instances of BMP failures. This has proven to be problematic for BMP expert panels when published data about BMP failure rates is so scarce. Basic data about inspection failure rates would be a first step, and long term the inspection data - at least for priority BMPs - could perhaps include simple information regarding the cause or extent of the failure. Currently this data is absent in the published literature, and the foundation offered by CBP partnership's BMP verification framework would enable the jurisdictions and the CBP to fill a significant gap in the knowledge base about BMP longevity.
2. <u>Encourage and incentivize partnerships between researchers and jurisdictions' BMP verification programs to collect and publish more long-term BMP performance data.</u> When the CBP adopted its <u>BMP Verification Framework</u> it included a note about a future desire to leverage data collection opportunities through verification site-visits or inspections, or other methods, to also gather BMP performance data (page 49-50 of framework document). No such effort materialized, likely due to a lack of resources and capacity, in

addition to a large number of competing science needs and priorities. There may be opportunities to more directly encourage researchers and experts to partner with jurisdictional agencies to confidentially collect and assess BMP performance data for subsequent publication. To the extent that BMP performance data is already encouraged or collected through funding mechanisms or partnerships, the CBP should ensure that any BMP performance data is periodically published in a searchable database or publicly accessible report that can be used by interested researchers, and would include data fields as suggested by Liu et al. (2017) among others.

3. More mechanistic BMP modeling studies. Develop more mechanistic modeling of individual (or suites of) BMPs under baseline and altered climatic conditions. Current CBP modeling efforts are better suited to represent how climate change might influence nonpoint source pollution loads reaching BMPs by representing a change in generation, transport, and–to some extent–storage within the landscape. The influence of predicted changes in land use and management decisions in both agricultural and urban settings on N, P, and sediment loading is an area of active research also captured in simulation models.
4. Leverage existing adaptive management efforts to establish a CBP agenda for research and science needs related to BMPs and climate change, with priority on communication of "no-lose" directions. There are long-standing and ongoing efforts within the CBP to better articulate and understand the state of knowledge and research needs pertaining to BMPs in a changing climate. This report grew from such discussions and the concepts, findings and recommendations documented here will augment the CBP's efforts moving forward. The details and direction of the research agenda are the prerogative of the CBP partnership, not the authors of this study, but it is recommended that the CBP utilize its network of experts and communications professionals to identify and communicate strategies that have zero or minimal chance of negative impacts. For example, the protection and conservation of existing high-functioning natural areas will remain an effective strategy for water quality and numerous other environmental outcomes regardless of future climate conditions.
5. Develop mechanisms of quantifying BMP efficiency uncertainty under climate change. The evolution of the watershed model makes analysis of multiple potential outcomes relatively straightforward. In this context, it becomes possible to consider the implications of BMP performance uncertainty by assuming and simulating alternative efficiencies.
6. Expert elicitation to determine alterations to BMP Efficiencies. The CBP partnership has an urgent need to account for the impact that climate change may have on BMPs' effectiveness, but the uncertainty in performance extends to management and other complex non-climate factors which are poorly understood in the literature for most BMPs. Without accounting for climate impacts and performance uncertainty the CBP may not be setting realistic expectations of BMP implementation necessary to achieve water quality goals under future climate conditions. However, the information needed to simulate these factors is not available in the literature, as seen through this synthesis. The CBP can still gather the necessary information, with expert elicitation likely to be the most cost-effective, robust and timely option would be a comprehensive expert elicitation project that would encompass all existing BMPs.

Table of Contents

Overview

Achieving water quality goals in the Chesapeake Bay under climate change will depend on robust landscape management strategies. Best management practices (BMPs) that reduce nutrient and sediment export effectively across a range of possible future climates will be a critical part of such strategies. Selection and targeted implementation of BMPs robust to climate change impacts requires understanding of the factors influencing BMP performance variability as well as the uncertainty in predicted climatic conditions and how these affect (1) the hydrologic and biogeochemical processes that control the cycling of nutrients and sediments through the watershed, (2) the land use changes and management decisions affecting export of nutrients and sediments, and (3) the efficacy, efficiency, and cost-effectiveness of BMPs intended to mitigate nutrient and sediment export. We synthesize the science of the impacts of climate change on watershed nutrient and sediment cycling and to identify the mechanisms by which climate change can affect BMP removal efficiency, performance uncertainty, and, ultimately, nutrient and sediment loading to the Bay. We applied a modified systematic review methodology to answer two specific questions.

1. How do climate change and variability affect nutrient/sediment cycling in the watershed?
2. How do climate change and variability affect BMP performance?
    a. By what mechanisms can climate change and variability affect BMP nutrient and sediment removal efficiency?
    b. How does climate change affect BMP performance variability?

The ultimate goal of addressing these questions is to help decision makers determine which BMPs will likely result in the best water quality outcomes under climate uncertainty

We conceptualized these research questions by expanding a simplified nutrient and sediment material balance to represent the impact of climate change and variability on nutrient and sediment loading to the Bay (Figure 1). The review identifies which climate change variables and affected processes have the greatest impact on nutrient and sediment loads and load reductions by agricultural, urban, and assimilative BMPs and where knowledge gaps persist. The uncertainty in climate projections of such critical variables and the uncertainty in impacts of these variables on watershed processes and remediation efforts was characterized.

Question 1: How do climate change and variability affect nutrient/sediment cycling in the watershed? The foundation of the systematic review evaluated observational and modeling studies in the Chesapeake Bay watershed that assess the impact of climate change and/or variability on watershed hydrology, and nutrient and sediment cycling (i.e., transport, storage, and nutrient species transformations) and predict nitrogen (N), phosphorus (P), and/or sediment loads. Since the review of (Najjar et al. 2010) the scientific literature on climate change and its impact on nutrient and sediment cycling in the Bay watershed has grown significantly and is sufficient to support this review. To extract data from these studies, we cataloged and categorized the attributes of inputs/methods (e.g., climate scenarios, global climate models, downscaling technique, watershed models, spatial and temporal scale) and outputs/metrics (e.g., forecast N/P/sediment loads, model skill, rate change in some biogeochemical process) of these studies to assess the relationships between study attributes and variability/uncertainty in predictions of N, P, and/or sediment loading. Using the generated database describing study methodologies and their findings, we assessed the relationships between attributes of study design and uncertainty/ variability in predictions of N, P, and sediment loading as well as characterize output variability across all studies to evaluate the relative uncertainty/variability.

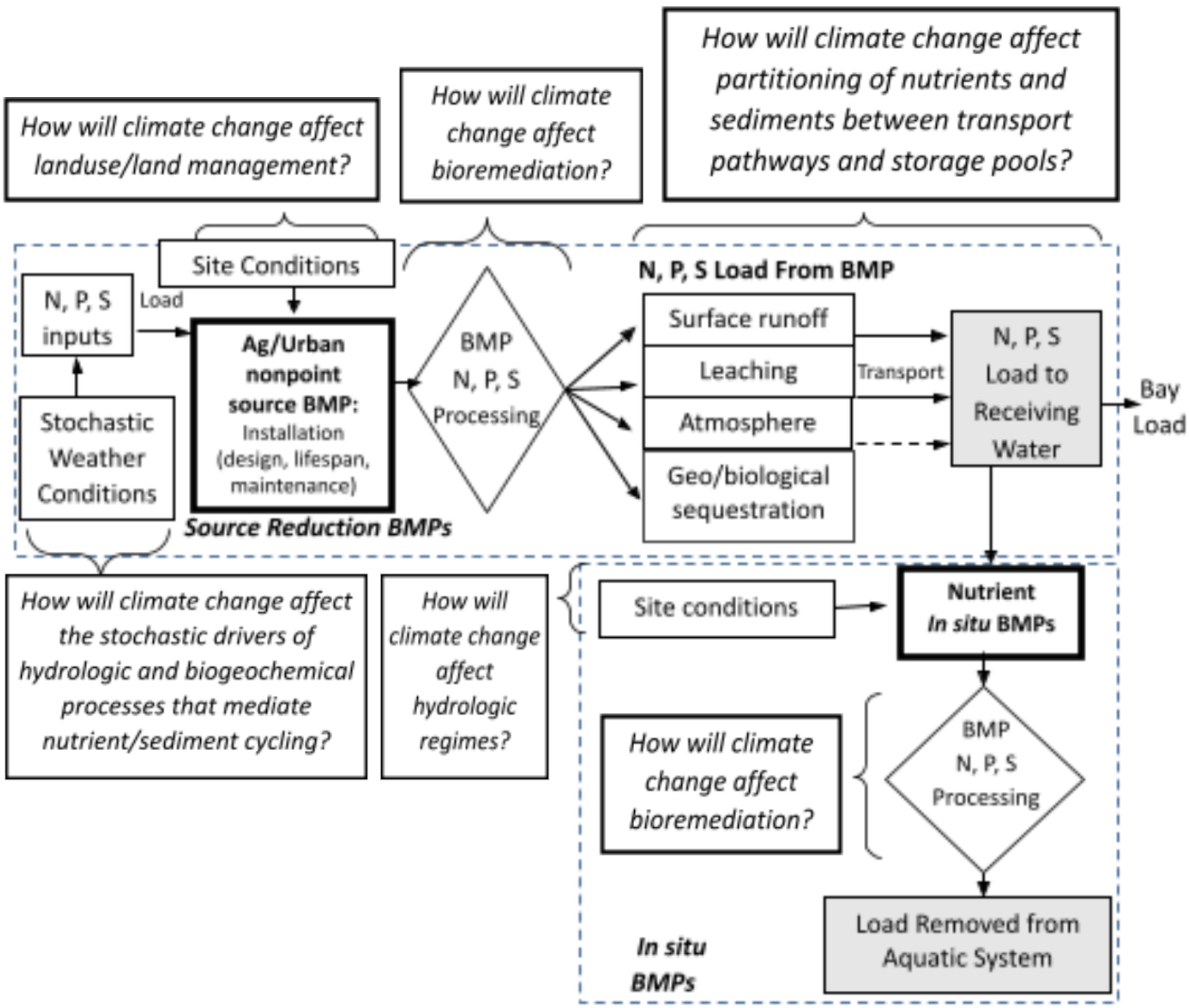


Figure 1: A simplified material balance for nutrient and sediment control BMPs overlaid with a conceptual model of how climate change influences BMP performance and nutrient/sediment cycling and transport to the Bay. In situ BMPs refer to those that remove nutrients and sediment directly from surface waters (e.g., stream restoration), as opposed to source reduction BMPs, which intercept pollutants before they reach water bodies (e.g., cover cropping, nutrient management).

Question 2: How do climate change and variability affect BMP performance? We divided this question into two focus areas, one addressing the mechanisms by which climate change affects BMP effectiveness and the other addressing how climate related uncertainty translates to BMP performance uncertainty. We primarily draw on two sources of data, the climate change/ watershed simulation studies that explicitly evaluate the effect of BMPs and reports by the Chesapeake Bay Program (CBP) BMP Expert Review Panels. We create an attribute table for the simulation studies expanded to include attributes of BMPs application (e.g., removal process representation, design assumptions). However, due to the small number of studies in this area, it proved difficult to reveal relationships analogously to the approach in Question 1, though the literature on the impacts of climate change on BMP performance is growing. We also identified the dominant variables that influence BMP performance using the Expert Review Panel findings as a starting point and prioritized searches for additional data examining the effects of the identified critical variables or addressing data gaps according to the BMP conceptual model. By examining the overlap between the most important variables/processes influencing BMP performance and the variables/processes most influenced by climate change and variability, we identified the mechanisms by which climate change is most likely to influence BMP performance. We evaluated the effect of climate variability/uncertainty on the variability in BMP performance through an examination of why climate variability/uncertainty is influential. Through mechanistic understanding of the most influential and/or uncertain climate variables combined with knowledge of the dominant variables dictating BMP performance (as derived from this review), we were able to evaluate how climate change and variability are most likely to affect BMP performance variability, both for individual practices and relatively across practices.

An understanding of BMP robustness is critical because certain practices that perform well under one climate scenario might prove to be maladaptive under another. A key aspect of the synthesis determined the relative sensitivity of BMPs to environmental variables impacted by climate change in order to identify robust solutions. This was accomplished by examining the combined effects of climate change on BMP central tendency and variability as evaluated in Question 2 and considering reported cost-effectiveness based on available unit cost estimates in CAST. We evaluated approaches appropriate for assigning relative levels of uncertainty to BMPs that are capable of incorporating both climate and performance uncertainty and suggested different metrics to describe robustness, such as lack of data on BMP performance probability distributions and well-defined quantitative relationships between performance and controlling variables was a major consideration (<1/3 of the Expert Review Panels provided some indication of BMP variability, often qualitatively); thus, one aspect of defining robustness involved an assessment of the strength of evidence. A critical project outcome will be identifying knowledge gaps that future research must address to answer this question; we may not know enough about a particular BMP’s function to evaluate if it is robust to climate changes.

Descriptions of terms

Climate factors: temperature, precipitation, CO_2, solar radiation, potential evapotranspiration,

Hydrologic response variables: streamflow/runoff, soil moisture, actual evapotranspiration

Watershed processes and response variables: processes describing N, P, and sediment cycling, and response variables describing the resultant loads

BMP resilience: not a term used until later in this section (discussion, conclusions). "BMP resilience" could be considered in a variety of ways, but for this report "resilience" of a BMP refers to that BMP's ability to deliver and maintain water quality benefits at an expected level or within an expected range given current or future conditions.

BMP implementation in the watershed, 1985 - present

The Bay jurisdictions report BMP implementation annually to the Chesapeake Bay Program. These BMPs are reported at various scales, including specific latitude-longitude coordinates, varying watersheds (HUC-4, -6, -8, -10 or -12), county or statewide (watershed CBW portion only). The BMPs are combined with base conditions data generated by the partnership using agreed-upon methods to estimate animal populations and other inputs using data available to the CBP partners. For detailed information, consult the Chesapeake Assessment Scenario Tool (CAST) website (https://cast.chesapeakebay.net/), which houses all model documentation as well as extensive data and documentation for inputs and methodologies applied in the Watershed Model.

There is available annual BMP implementation data from the bay jurisdictions dating back to 1985. The annual implementation data includes all CBP-approved BMPs, which use a variety of measurement units, including, but not limited to: acres, feet, animal count, animal units, and pounds. Practices take many forms. For the purposes of this report, BMPs are often discussed in terms of structural BMPs or management BMPs. Structural BMPs are most commonly multi-year practices as they are built or installed to last for longer periods of time, and sometimes indefinitely. While we use the term "structural" we are not exclusively referring to gray or built structures. Many structural practices can be green, nature-based systems, or be hybrids of green and gray structures. We simplify by using the term "structural" to refer to any practice that continues to operate or function within the landscape for multiple years following its initial construction, installation or planting. There may be instances where a structural practice is mobile, but these are rare or only exist on pilot-scales. "Management BMPs" may be a redundant term, but it is intended to define a class of practices that are less dependent on built or planted structures and more dependent on active or passive management by a person(s). These practices are often, but not always, performed on an annual basis.

The watershed model includes two types of BMPs based on their simulated duration: annual and cumulative. In CAST, annual practices are any BMP that is implemented and simulated only for a single year, whereas cumulative BMPs last more than one year and can remain in simulated scenarios for multiple years. CAST itself only runs single year scenarios, but it is useful to know the distinction between annual and cumulative BMPs when looking at implementation data over time. The following chart (Figure 2) considers three popular annual BMPs - agricultural nutrient management, cover crops (traditional only), and conservation tillage (all types defined by the CBP) - in comparison to all other annual BMPs that are also reported in acres, which includes all sectors not only agriculture (source: CAST, trends over time data).

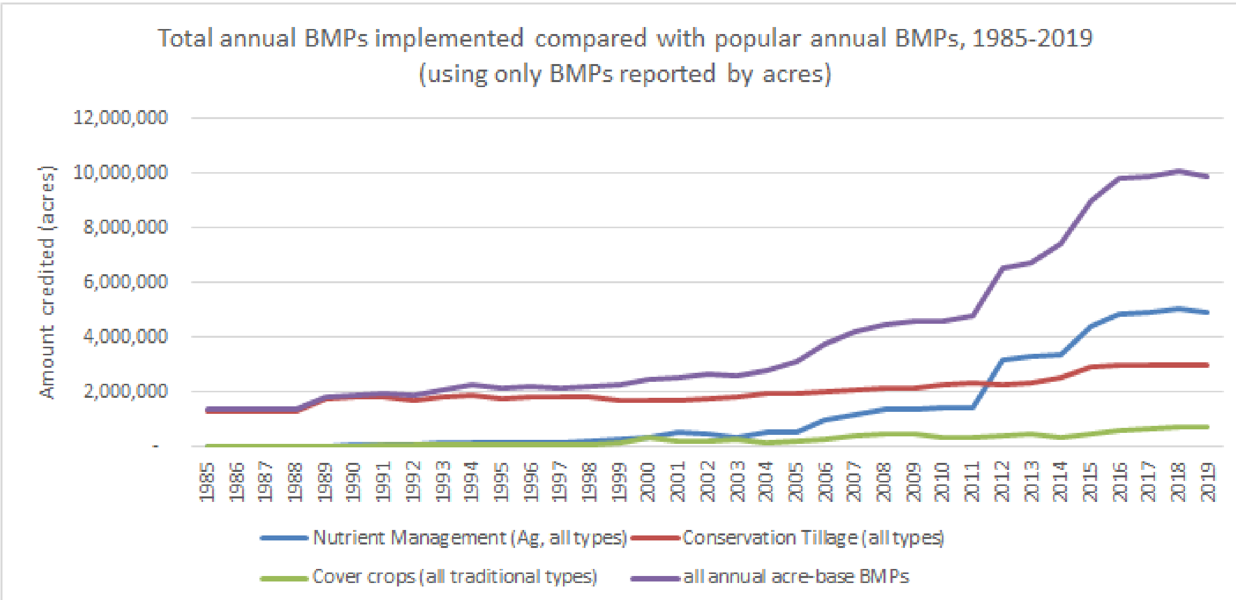


Figure 2. Total annual BMPs implemented compared to three popular annual BMPs, 1985-2019, only looking at BMPs in acres. Source: CAST (2019), trends over time data download. Accessed October 2021.

For comparison, Figure 3 looks at cumulative practices that are also reported by acres. While the annual practices are composed largely of the popular practices also graphed in the previous previous, there is a greater diversity of cumulative practices. To simplify the chart, the cumulative practices are shown by two sectors (agriculture and urban) and the net total (which also includes practices in the “natural” sector as defined in CAST). Agriculture represents the large majority of cumulative practices implemented in the watershed

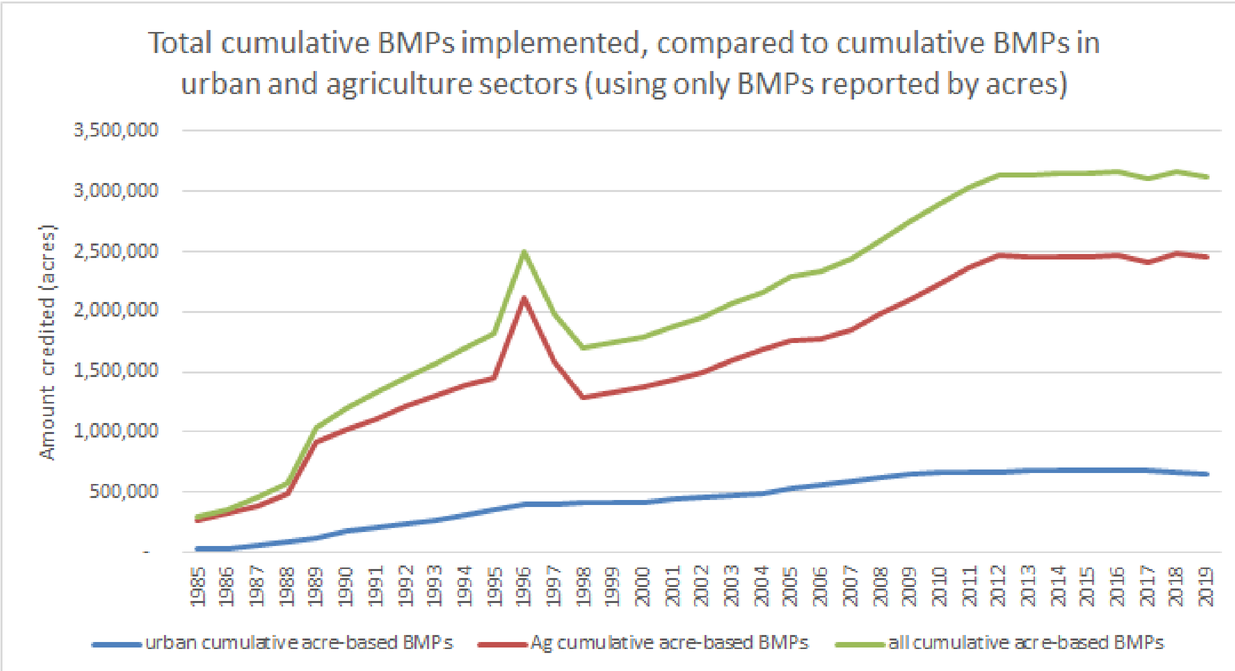


Figure 3. Total cumulative BMPs implemented, compared with urban and agriculture sector cumulative BMPs, 1985-2019, using only BMPs reported in acres. Source: CAST (2019), trends over time data download. Accessed October 2021.

Many other practices are reported in other units, so it can be difficult to compare levels of implementation and relative effect across sectors and across all BMPs. The chart below, from Chesapeake Bay Program (2020), shows the most-implemented practices based on the planned implementation levels in the jurisdictions Phase 3 WIPs, and it includes BMPs that are measured in other units, not just acres (x-axis displayed in logarithmic scale of amount credited).

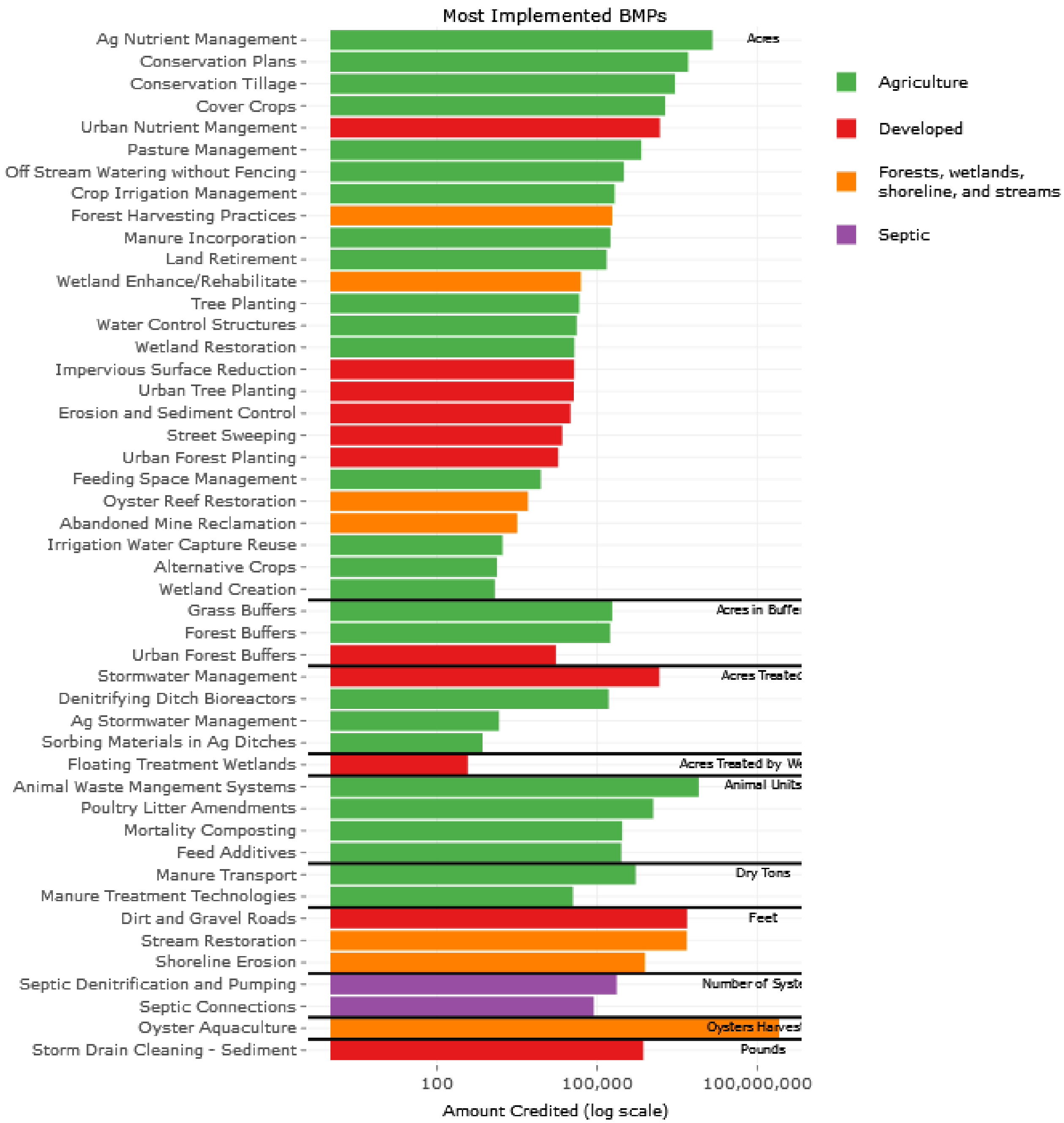


Figure 4. Most Implemented BMPs, across source sectors and reporting units. Source: CAST (2019). https://cast.chesapeakebay.net/Documentation/wipbmpcharts

To understand the overall effects of BMPs, annual scenarios from CAST can compare “no action” scenarios to the official Progress scenario of each year. Using the reported wastewater data from each given year in the “no action” scenario controls for the point source loads and reductions, yielding an estimate of the overall impact of all BMPs implemented in that year. The overall impact of all nonpoint source BMPs, for all sectors and across the whole CB watershed is given as a percentage estimate for N, P and sediment in Figure 5.

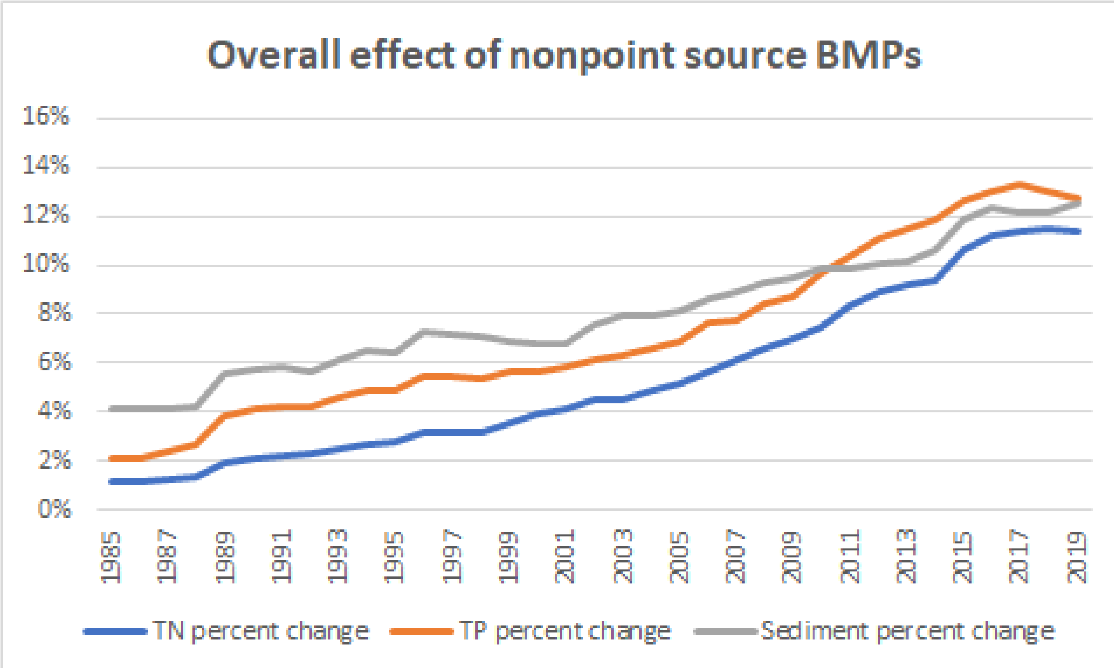


Figure 5. Estimated effect of all BMPs in annual progress scenarios, 1985-2019. The effect from wastewater treatment plant reductions is not included in this analysis. Data downloaded from CAST annual progress scenarios, compared with no-action scenarios of the same year to calculate change in loads and % difference. Chesapeake Bay Program (2020), CAST 2019.

Note that the percent values in Figure 5 are calculated as a percent *reduction*, even though the values are shown as positive. For example, all BMPs reported and simulated in 2017 reduced total P loads by ~13% from the "no action" baseline, whereas all BMPs reported and simulated in 1985 only reduced total P loads by ~2%. The increasing overall reductions reflects the increasing levels of implementation across the watershed, even though the baseline also shifts due to land use change, population growth and other factors. Since this estimated effect is calculated from CAST scenarios it represents the accumulated reductions of BMPs using an average hydrology and with specified effectiveness values for each simulated BMP. This is useful to compare the relative influence of BMPs over time, but a look at summarized observed conditions over time (Table 1; CAST, 2019; Murphy et al. 2019) across the watershed's 130 monitoring stations shows that TN and TP loads are improving at a smaller percentage of sites in recent years compared to the long term trend. The differences between the short term and long term trends are less severe when flow-adjusted. Figure 6 and Table 2 provide some context and contrast between model-predicted improvements from nonpoint source BMPs and measured water quality. The modeled results will inevitably vary due to lag times (Meals et al. 2010), among other factors. Differences between measured results and modeled predictions will be discussed later with respect to BMP studies.

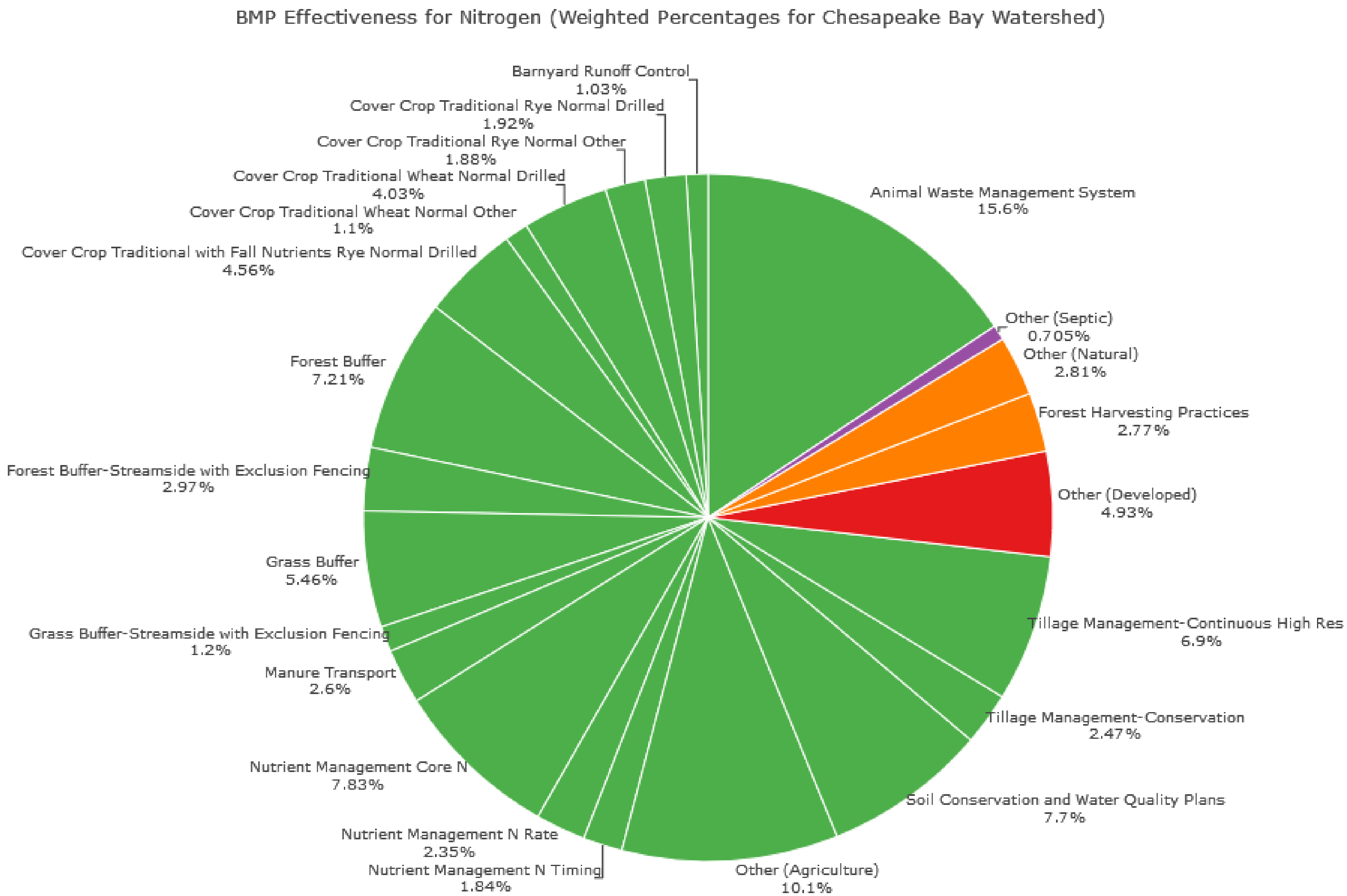
Table 1. Short and long term trends in estuary dissolved oxygen, Secchi depth, Chlorophyll-a, Total Nitrogen and Total Phosphorus. From CAST (2019) estuary trends https://cast.chesapeakebay.net/TrendsOverTime. Data and procedures from Murphy et al. (2019).

Water Quality Variable	**Observed Conditions**			**Flow-adjusted Conditions**		
	Improving	**No Change**	**Degrading**	**Improving**	**No Change**	**Degrading**
Short-term Trend (2010-11 to 2018-19)						
Dissolved Oxygen (summer, bottom layer)	22%	62%	16%	21%	56%	24%
Secchi Depth (annual, surface layer)	13%	58%	29%	27%	48%	25%
Chlorophyll-a (spring, surface layer)	26%	65%	9%	28%	63%	10%
Total Nitrogen (annual, surface layer)	16%	49%	35%	46%	40%	14%
Total Phosphorus (annual, surface layer)	29%	54%	17%	43%	49%	9%
Long-term Trend (Period of Record)						
Dissolved Oxygen (Summer, bottom layer)	30%	47%	24%	24%	44%	32%
Secchi Depth (annual, surface layer)	12%	20%	68%	18%	25%	57%
Chlorophyll-a (spring, surface layer)	20%	38%	42%	27%	45%	28%
Total Nitrogen (annual, surface layer)	68%	18%	14%	88%	10%	1%
Total Phosphorus (annual, surface layer)	76%	13%	12%	81%	14%	5%

Planned implementation and relative contributions of BMP categories; Identification of BMPs

The previous section presented the overall reported BMP implementation since 1985 and the overall effect of that implementation. Figure 6 considers the planned implementation in the jurisdictions Phase 3 WIPs, and illustrates the relative contributions of various practices. The first version shows the contribution of practices to the planned TN reductions and the second image for TP.

Given the large number of CBP-approved BMPs, this project attempted to focus its efforts on certain selected practices. A number of sources informed the generation of the list in Table 2 below. Sekellick et al. (2019) served as an initial source, with input from CBP stakeholders also provided alongside the planned implementation and relative reductions as seen in Figure 6, respectively. Additional funding from NOAA specifically asked for a literature search targeting certain practices associated with vital habitat and living resource concerns, often but not exclusively in tidal areas.



BMP Effectiveness for Nitrogen (Weighted Percentages for Chesapeake Bay Watershed)
Barnyard Runoff Control 1.03%
Cover Crop Traditional Rye Normal Drilled 1.92%
Cover Crop Traditional Rye Normal Other 1.88%
Cover Crop Traditional Wheat Normal Drilled 4.03%
Cover Crop Traditional Wheat Normal Other 1.1%
Cover Crop Traditional with Fall Nutrients Rye Normal Drilled 4.56%
Forest Buffer 7.21%
Forest Buffer-Streamside with Exclusion Fencing 2.97%
Grass Buffer 5.46%
Grass Buffer-Streamside with Exclusion Fencing 1.2%
Manure Transport 2.6%
Nutrient Management Core N 7.83%
Nutrient Management N Rate 2.35%
Nutrient Management N Timing 1.84%
Other (Agriculture) 10.1%
Soil Conservation and Water Quality Plans 7.7%
Tillage Management-Conservation 2.47%
Tillage Management-Continuous High Res 6.9%
Other (Developed) 4.93%
Forest Harvesting Practices 2.77%
Other (Natural) 2.81%
Other (Septic) 0.705%
Animal Waste Management System 15.6%

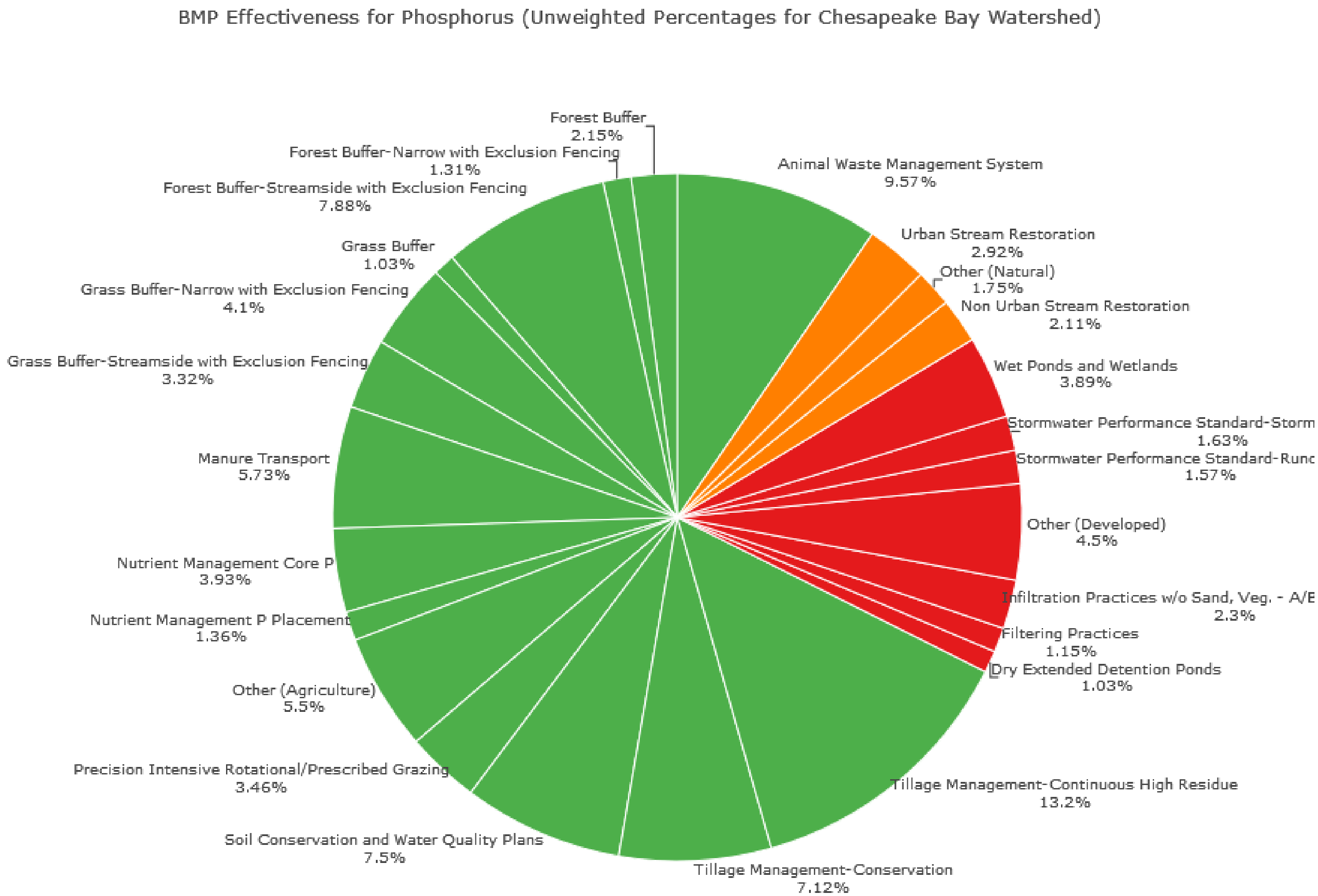


Figure 6. BMP Effectiveness for nitrogen (top) and phosphorus (bottom), showing weighted percentages for Chesapeake Bay Watershed that represent relative reductions from nonpoint source BMPs in jurisdictions' Phase 3 Watershed Implementation Plans. Source: CAST, 2019. Accessed October 2021. https://cast.chesapeakebay.net/Documentation/wipbmpcharts

It must be emphasized that the practices evaluated do not reflect the social or environmental value of a BMP, but only reflect estimated contributions in the WIPs and/or specific requests from CBP workgroups to include in the analysis. In discussions with CBP groups such as the CLimate Resiliency Workgroup and Water Quality Goal Implementation Team, there was interest to prioritize multi-year BMPs that contribute substantially to WIP reductions as well as structural BMPs that persist for longer time periods in the landscape. However, as seen in the next section of this report, we also include practices by virtue of their presence in the reviewed literature (e.g., filter strips), and/or if the practices logically fit with conceptual models of the next section, or based on the authors' familiarity with the BMPs for the sake of examples.

Table 2. Overview of BMPs considered as priorities for the literature searches based on reported or planned implementation, effectiveness, partnership input, or based on natural and habitat considerations from NOAA.

Most implemented	**Most effective TN**	**Most Effective TP**	**Tidal BMPs**
By units planned implementation/treatment	By reductions	By reduction	
Ag Nutrient Management	AWMS	AWMS	Living shoreline
Tillage Management	Tillage Management	Tillage Management	Tidal wetland restoration
Cover Crops	Nutrient Management	Forest Buffers	Oyster restoration
Urban Nutrient Management	Forest Buffers	Grass Buffers	Oyster aquaculture
Pasture Management	Grass Buffers	Nutrient Management	
Forest Harvesting	Cover Crops	Stream Restoration	
Manure Incorporation		Wet Ponds and Wetlands	
Land Retirement			
Wetland Rehabilitation			
Tree Planting			
Wetland Restoration			
Grass Buffers			
Forest Buffers			
Animal Waste Management Systems (AWMS)			

Ultimately, this report found varying levels of information for the above practices, in addition to information about a range of other BMPs included in the literature results. The methods and results are summarized in the next section.

Climate Change: An Overview

Climate change poses an array of challenges to meeting the Bay TMDL nutrient/sediment reduction targets. Some of these challenges, such as increased streamflow, are widely recognized for their potential to increase nutrient/sediment delivery to the Bay. Indeed, the TMDL Phase III Watershed Implementation Plans (WIPs) now requires all Bay jurisdictions to account for the additional nutrient and sediment loading expected from climate change through 2025. In order to understand how climate change is affecting system response at the Bay level, it is important to characterize the ways in which climate-induced changes to the watershed may be affecting management actions implemented to achieve the Bay TMDL (a description the TMDL can be found in the Appendix).

The primary climate-related drivers affecting the Bay watershed are air temperature and precipitation (Johnson et al. 2016, 2018). Other climatic variables, including sea-level rise, humidity, radiation, and atmospheric carbon dioxide (CO_2) concentrations may be important to consider as well. Changes in these drivers are expected to alter key processes within the Chesapeake Bay and its watershed, including evapotranspiration (ET), plant growth, soil moisture, streamflow, terrestrial and aquatic biogeochemistry, water temperature, salinity, estuarine circulation, and water quality variables such as water clarity, chlorophyll-a, and dissolved oxygen (Najjar et al. 2010). Climate change will also affect water quality by indirect means, such as by increasing the length of the growing season, which can result in changes in agricultural land use, and increasing the opportunity for agricultural intensification, such as double cropping. This could fundamentally alter the nutrient mass balance, and as a consequence the cycling and export of nutrients in ways we do not fully understand. Increased stream temperature is already thought to have decreased N export from portions of the watershed due to increased denitrification (Chanat and Yang 2018), though increased stream temperature has other consequences for the aquatic ecosystems.

Precipitation is one of the key climatic variables that not only controls watershed discharge, but also influences internal nutrient cycling processes, and the potential for increased nutrient/sediment export from the watershed. Climate predictions suggest that precipitation quantity (during the winter/spring), and intensity (during the growing season) will continue to increase,which causes greater diffuse nutrient and sediment export from agricultural landscapes (Chang et al. 2001; Cousino et al. 2015), as well as developed areas. This increased export has a number of deleterious consequences for receiving water bodies; accelerated eutrophication resulting in harmful algal blooms (Burgin and Hamilton 2007), undesirable changes in the river structure and function, and decreasing storage capacity or flood control of reservoirs (Cerco 2016; DePhilip and Moberg 2010). In addition, the loss of valuable nutrients and topsoil from agricultural fields decreases productivity or increases management intensity (Lal 1998). According to Easterling et al. (2017), mean annual precipitation in the Mid-Atlantic region increased by 5–10% from the historical period (1901–1960) to 2015. These findings dovetailed with recent observations by Rice, Moyer, and Mills (2017) showing that precipitation increased throughout the Bay watershed from 1927–2014, with northern regions of the watershed exhibiting increases on the order of 6–15%. Notably, studies by Sinha and Michalak

(2016) and Ballard, Sinha, and Michalak (2019) indicated strong linkages between increasing precipitation and N export to the Bay. Moreover, a study by Ryberg et al. (2018) suggested that annual precipitation was a key driver of P loads to the Bay, and that increases in precipitation could already be offsetting management actions to reduce P loss (Ockenden et al. 2016, 2017). In cases where increasing precipitation is enhancing nutrient loading to the Bay (Ballard et al. 2019), jurisdictions might need to implement additional management practices to mitigate these trends (Rice et al. 2017; Ryberg et al. 2018), as indicated in the Phase III WIPs.

It is important to note, however, that aggregate trends in precipitation do not reflect changes in rainfall distributions, particularly the duration, frequency, and magnitude of extreme events, or how precipitation is distributed across the watershed. For example, precipitation intensity has been on the rise in the US (Mallakpour and Villarini 2017) and throughout the Northeast (Huang et al. 2017). According to Easterling et al. (2017), the amount of annual precipitation falling in the heaviest 1% of daily events increased by 55% in the northeastern US, faster than any other region in the nation. Johnson et al. (2016, 2018) report that by mid century, the mean increase in precipitation intensity (defined as the number of days per year with precipitation above 1 inch) is 10 and 20% throughout the Chesapeake Bay watershed. These changes in precipitation intensity can affect patterns and magnitudes of nutrient and sediment loss. Not surprisingly, nutrient losses from extreme precipitation have important implications for nonpoint source BMP performance (Renkenberger et al. 2017), as increased runoff generation, can overwhelm BMP infrastructure (Moglen and Rios Vidal 2014) and potentially diminishes nutrient load reductions from BMPs (Hopkins et al. 2017; Selbig and Bannerman 2008).

Temperature has a large effect on the system through impacts on ET (which influences soil moisture and streamflow), water temperature, and on biogeochemical processes (e.g., denitrification) among others. In the assessment by Johnson et al. (2018) of climate data for use in the CBP modeling framework, they found that air temperatures predicted by 15 climate models show an increase of + 1.6 C by 2035, and average warmings of +2.7 C to + 4.4 C towards the end of the century. These increases in air temperature affect watershed and BMP function directly, through changes to ET and soil moisture, and indirectly via changes to biogeochemical cycling rates, plant growth rates, or plant water use (Modi et al. 2021). Adding complexity to how climate change impacts terrestrial processes is the interaction between temperature and precipitation, for instance, BMPs such as riparian buffers or cover crops may be least impacted under scenarios of moderate warming without significant shifts in the timing or magnitude of precipitation but result in reduced growth (and degraded BMP performance) if dry periods coincide with times when plants are most sensitive to water shortages (Elliott et al. 2014). Water temperature may also have direct effects on BMP performance, such as for wetlands where temperature influences both plant growth and nutrient cycling and uptake (Kadlec and Reddy 2001).

In addition to changing temperature and precipitation, atmospheric CO_2 concentrations play a crucial role in plant water use and growth (Modi et al. 2021), both of which can influence how BMPs perform. Increased atmospheric CO_2 levels can increase agricultural productivity by enhancing photosynthesis rates while suppressing leaf-level transpiration, ultimately reducing plant water use (Kimball and Idso 1983; Vanuytrecht et al. 2012). However, the interactions between changes in precipitation, temperature, atmospheric CO_2 concentrations, and plant/vadose zone processes make collecting empirical evidence of the impact of climate change on BMPs that harness plant based nutrient removal highly uncertain. Thus, most of the studies included in the review that account for the CO_2 fertilization effect rely on models, adding additional uncertainty.

Nutrients and Sediment

Nutrient export from the landscape to surface waters is controlled by a combination of key biogeochemical and hydrologic processes. Changes in precipitation and temperature alter the timing and magnitude of runoff, soil moisture, and biogeochemical cycles (Gleick 1989). For instance, N mineralization, nitrification, and denitrification are, to a large extent, controlled by factors that climate change influences, such as soil temperature, soil moisture, and carbon availability (Butterbach-Bahl and Dannenmann 2011). Wagena et al. (2018) report that climate change caused an increase to the rate of nitrification (conversion of ammonium to nitrate), and a reduction on denitrification (conversion of nitrate to nitrogen gas), ultimately providing a greater pool of soluble N in an agricultural watershed. During the winter and spring, the increase in nitrification provided more NO_3 to the system than could be utilized by denitrification because this system was C limited. This process is driven by increased temperatures, soil moisture levels, and soil N levels. Similarly, increased soil temperatures and moisture content can influence the sorption and desorption of P, as well as immobilization and mineralization rates, all factors affecting P export (Sheppard and Racz 1984). Increased soil temperature can accelerate the growth of soil microbes (Davidson and Janssens 2006) that control nutrient processes such as nitrification, denitrification, and P mineralization. These processes are primarily controlled by soil and environmental factors that are affected by a changing climate (Parton et al. 1996). All of these derivative hydrologic changes impact nutrient cycling as well (Huntington 2003; Johnson et al. 2012; Najjar et al. 2009, 2010; Neff et al. 2000). It is also well established that sediment transport is affected by soil moisture (Wiggs et al. 2004), by precipitation amount, and by precipitation intensity (Römkens et al. 2002), most of which are predicted to increase in the Bay watershed.

Non-point sources are the primary contributor of nutrients and sediment in the Chesapeake Bay region and cause numerous problems when they enter water bodies, such as eutrophication (Sharpley et al. 2003), reduced dissolved oxygen, fish kills, loss of biodiversity, and human health threats (Carpenter et al. 1998; Peterjohn and Correll 1984). BMPs are increasingly and widely used to reduce the impact of diffuse pollutant export from agricultural landscapes and improve water quality (Ullrich and Volk 2009). BMPs can be structural or management based. Structural BMPs include physical structures, such as manure storage, or altered landscape features, such as stream restoration, while management BMPs involve altering some sort of landscape management practice, such as nutrient management, or conservation tillage. For instance, conservation tillage or no-till, enhances soil organic carbon, soil quality, and soil aggregation, leading to less soil erosion in agricultural landscapes (Roldán et al. 2007). BMPs such as riparian vegetation, strip crop, and buffer strip can all help reduce diffuse pollutants, by reducing inputs to the crop, enhancing sequestration of nutrients in plant tissue, or reducing surface and subsurface losses due to hydrologic pathway alterations (Carpenter et al. 1998). For instance, increased precipitation volume and intensity may overwhelm many BMPs like riparian buffers, but higher temperatures, longer growing seasons, and more rainfall might cause that same buffer to mature more quickly, thus trapping more sediment and sequestering more nutrients. Thus, BMPs need to be assessed for performance under a changing climate (Hatfield and Prueger 2004; Peterjohn and Correll 1984).

A fundamental understanding of these coupled processes (hydrology and nutrient/sediment cycling) under a changing climate is critical to managing N, P, and sediment export from ecosystems to sensitive coastal zones. Development of effective landscape management strategies to improve water quality requires an understanding of how processes that regulate nutrient/sediment production on the landscape are coupled with hydrologic transport to water bodies. Of particular interest is the impact of climate change on hydrologically active areas of the landscape that contribute disproportionately to watershed nutrient export (e.g., Critical Source Areas, CSAs), where active hydrologic transport and high nutrient availability coincide (Groffman et al. 2009a, 2009b). A better understanding of climate change and its potential influence on landscape biogeochemistry can be used to develop new strategies for protecting coastal waters and their contributing watersheds from pollution. For instance, it is entirely possible that climate change would enhance some natural ecosystem services that protect water quality. One example is through a potential change in denitrification, a natural process that transforms dissolved NO_3-N into nitrogen gasses, and returns it to the atmosphere. Hydrologically active areas in the landscape prone to soil saturation are recognized as biogeochemical hotspots (McClain et al. 2003; Vidon et al. 2010) and understanding where these areas are, or will be under future conditions will help water quality managers more effectively locate BMPs in critical areas of the watershed.

How is Climate Change Quantified: Climate Models

While there have been attempts to harness the climate analog approach to quantify climate change (e.g., space for time substitution), most assessments of climate change incorporate use of general circulation models (also referred to as global climate models,GCMs) to quantify how climate may change over time and for given scenarios.

Climate models represent the past, present, and future climate trends by solving complex mathematical equations, which describe the physical processes and energy transfer between the land surface, ocean, sea ice, and the atmosphere (Bader et al. 2008). Major climate variables considered by most GCMs include precipitation, air temperature and atmospheric CO_2 concentration. Under the auspices of the United Nations, the World Climate Research Program (WCRP), the Coupled Model Intercomparison Project (CMIP) was introduced to promote coordinated climate modeling experiments — the aim of which is to better understand future climate changes induced by natural and man made changes to the atmosphere (Taylor et al. 2012). Since the scale of GCM predictions is relatively coarse (e.g., 1 deg to 3 deg latitude/longitude) downscaling is performed to better understand mesoscale phenomena —

Regional Climate Models (RCMs) are widely exploited for numerical downscaling, another approach is statistical downscaling; both are discussed further in Bader et al. (2008) and (Ross and Najjar (2019).

Global climate models compute the energy balance of the earth's atmosphere – the amount of radiation coming in and out of the earth's atmosphere. As presented in (Moss et al. 2010) this balance is affected by the concentration of radiatively active elements of the atmosphere – aerosols and greenhouse gasses. The change of their concentration over time is dependent on a myriad of factors including natural, socio-economic, technological, economic, and land use changes. Climate models require data on radiative pathway trajectory in order to predict changes in climatic variables. Accordingly, the IPCC has developed representative concentration pathways (RCPs), which capture the time evolution and end level alternative radiative forcing. Four RCPs for CMIP5 exist, (Figure 7): RCP8.5 (8.5W m^2 in 2100); RCP6.0 (6W m^2 at stabilization after 2100); RCP4.5 (4.5W m^2 at stabilization before 2100); RCP2.6 (Peak at 2.6W m^2 before 2100 and then declines) (Moss et al. 2010; Taylor et al. 2012).

Many earlier studies have employed CMIP3 projections (Nakicenovic and Swart 2000) and while the modeling methodologies are updated in CMIP5 the use of scenarios is similar, there are six radiative forcing levels for CMIP3, so called Special Report on Emission Scenarios, SRES (Figure 8). The most commonly used scenarios in the literature are the A2, A1B, and B1 scenarios typified by high, medium, and low future levels of atmospheric CO_2, respectively.

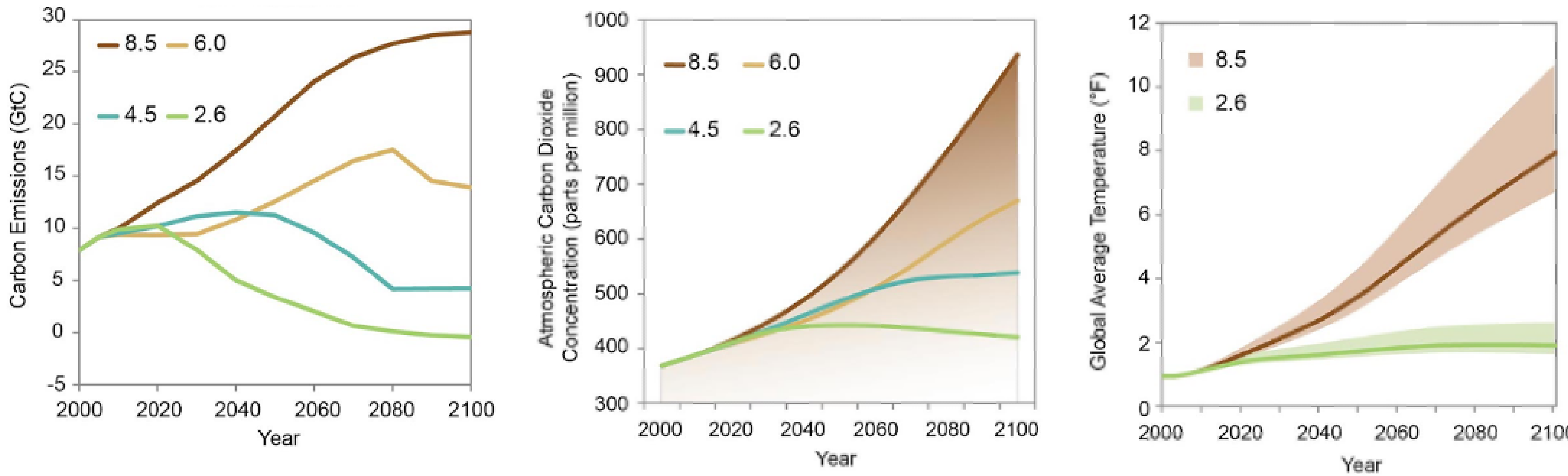


Figure 7. Coupled Model Intercomparison 5 (CMIP5) data showing global carbon emissions (left), atmospheric CO_2 concentrations (center) and average temperature (right) for different representative concentration pathways (RCP) over the period 2000-2100. Adapted from Walsh et al. (2014).

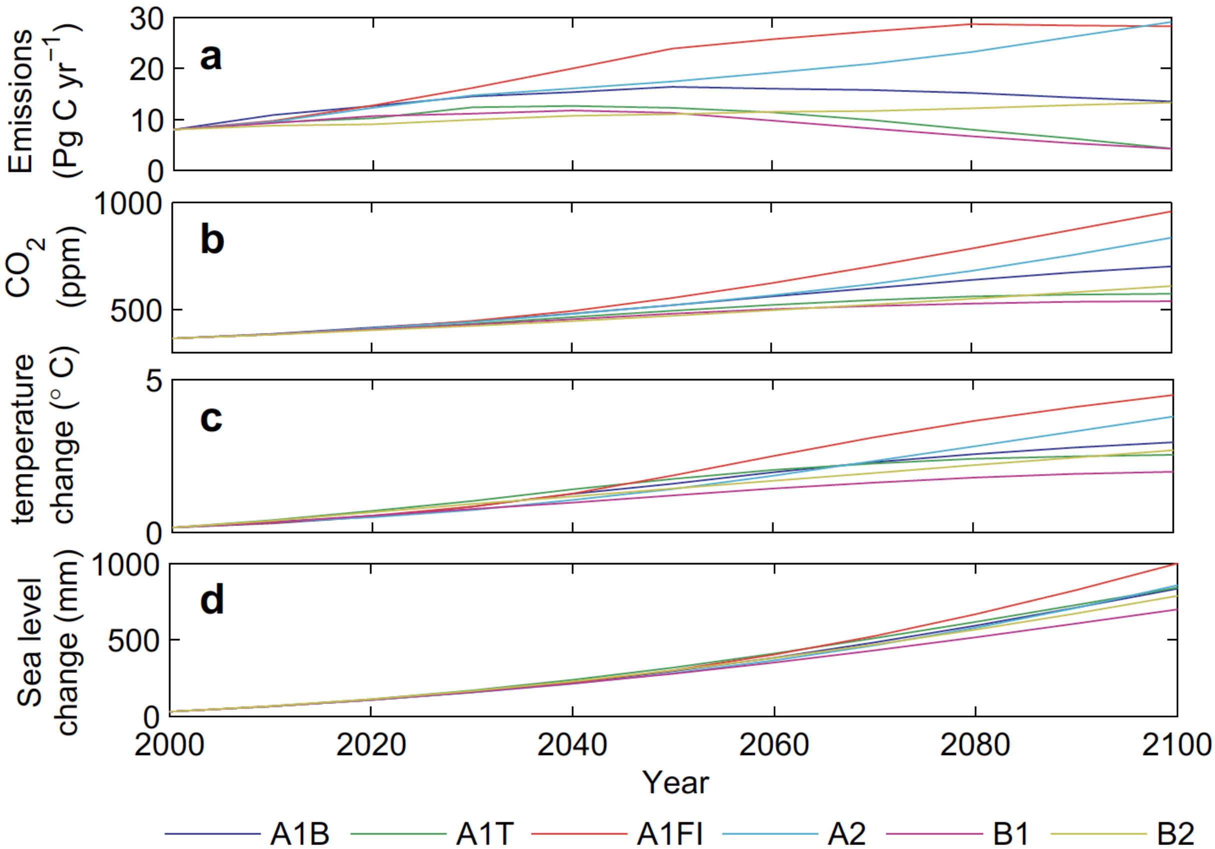


Figure 8. Coupled Model Intercomparison 3 (CMIP3) data showing global carbon emissions (a), atmospheric CO_2 concentrations (b) average temperature (c), and sea level rise (d) for different climate change scenarios over the period 2000-2100. From Najjar et al. (2010) and Houghton et al. (2001).

.

BMP Uncertainty

First we should distinguish between uncertainty and variability: variability describes the heterogeneity of response (say BMP performance), and is expressed with statistical metrics (mean, median, quartiles), it is a known quantity; uncertainty describes a lack of knowledge or an incomplete understanding or a response (e.g., what exactly the future climate may look like). Variability is often irreducible, an intrinsic state of the system, but uncertainty can be reduced with better or more complete understanding of the system.

There are a number of uncertainties involved in the assessment of climate change impacts on BMP performance. The mechanisms and processes by which BMPs reduce nutrient and sediment loads are biological or chemical, hydrological, and mechanical (as shown in the conceptual model in Figure 1), each of which may be impacted by climate change. These mechanisms determine the sensitivity of BMPs to different climate drivers (e.g., rainfall volume and intensity, temperature, soil moisture, etc.). Higher pollutant loading from urban and agricultural lands to BMPs could reduce BMP pollutant removal efficiencies, requiring resizing/redesign, or the need for additional BMPs to meet water quality goals (e.g., (USEPA 2018; Wagena and Easton 2018). Climate change could also alter physical and biological processes (e.g., denitrification) affecting the ability of BMPs to reduce pollutant loading. There are many nuances to this, for instance, climate change may induce altered delivery of nutrient and sediment loads that a BMP has to treat, but it may also affect changes to the BMP itself, and how it functions or performs. A given BMP could potentially remove a greater load of nutrients or sediment in a future climate, but have a lower efficiency (effectiveness) depending on how the delivered load changes. Figure 1 shows a simplified system material balance for a nutrient and sediment control BMP. BMPs receive nutrients and sediment inputs from a variety of sources. While weather events influence these inputs, the amount and composition of those inputs may not be well-known or characterized. Variation in BMPs performance is also heavily influenced by specific site conditions (slope, soil type, surrounding vegetation, etc.). Once pollutants enter the BMP, a number of pollutant transformation processes treat and reduce nutrients and sediment. In general, these processes can be chemical transformations (ex. nitrification, denitrification) or bio/physical sequestration (burial, storage in plants). Pollutants can be exported from BMPs through a variety of pathways in surface runoff, groundwater leaching, or through the atmosphere (N_2, N_2O, NH_4). The extent of loss pathways may be unknown or incompletely characterized. Finally, practices must be designed, installed, and maintained. Uncertainty in any of these components of BMP function may exist, and how removal pathways respond to different potential climates is an area of needed research.

One must also distinguish between the uncertainty of a BMPs existing performance, which often vary widely (Lintern et al. 2020), and those uncertainties introduced by the choice of climate model/scenario, or biophysical model. BMPs are designed and implemented with consideration of expected patterns of precipitation variability, including extreme events. In the decades to come, changes in climate present additional uncertainty and risk to BMP performance. Long-term changes in climate and extreme weather will have implications for BMP siting, design and maintenance strategies that seek to minimize a BMP's vulnerability to structural failure during its design life (Johnson et al. 2016, 2018). BMPs function through a variety of mechanisms, including physical retention (storage), filtration, chemical conversion, and biological uptake. These mechanisms determine the sensitivity of BMPs to different climate drivers (e.g., rainfall volume and intensity, temperature, soil moisture, etc.).

The Chesapeake Bay Program Watershed Modeling Framework

The CBP Phase 6 model shown in Figure 9, (also referred to as CAST) contains multiple components (landuse model, airshed model, watershed models and an estuary model). The watershed model (Figure 10) predicts loads of nitrogen, phosphorus and sediment delivered to rivers and streams, while accounting for the expected impact of BMPs on water quality.

Shenk et al. (2021) provide a concise description of the Phase 6 Watershed Model, which we paraphrase here. The Phase 6 Watershed Model consists of two parallel models: a time-averaged model and a dynamic model. The dynamic model is constrained to match the time-averaged model over the long term . The time-averaged model, known as the Chesapeake Assessment Scenario Tool (CAST), described in much greater depth in (Chesapeake Bay Program 2020), is used as the primary model for decision making at both the Bay Program and by jurisdictions. The dynamic model is used to produce hourly loads of nutrients and sediment for the estuarine model, as well as to assess scenarios, climate change and BMP efficiency among them.

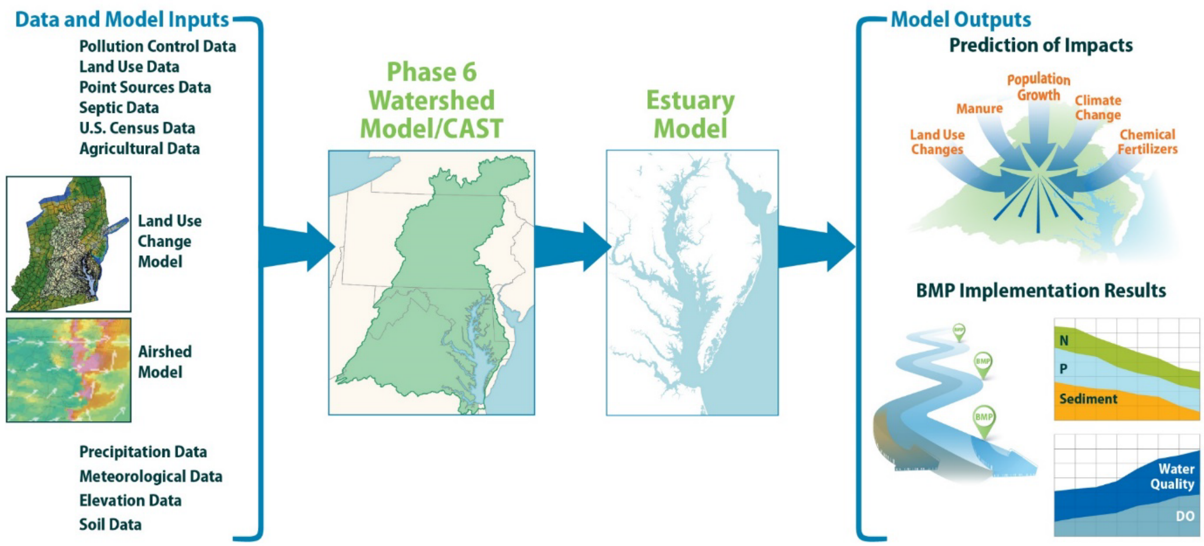


Figure 9. Chesapeake Bay Program partnership's modeling system (Shenk et al. 2021).

Best Management Practices in the Chesapeake Bay Watershed Model

Since 2010, the Chesapeake Bay Program (CBP) utilizes a partnership-approved expert panel process for estimating the nitrogen, phosphorus, and sediment reduction effectiveness of nonpoint source BMPs. In the process, panels of experts review scientific evidence and provide estimates of the nutrient and sediment removal effectiveness for individual BMPs. Chesapeake Bay Program (2015) details how BMP efficiencies are determined via the Expert Panel process and Stephenson et al. (2018) provide an explicit description of how BMP performance and performance variability are considered in CAST. Distilling these two documents, an estimate of BMP performance variability is not generally made by panels, and if those estimates are made the mechanisms to incorporate them into the model (CAST) are not currently in place (Stephenson et al. 2018) .

With regards to the BMP efficiency estimates made by expert panels, they are used in different ways: The CBP uses them to track progress toward meeting water quality objectives, and state and local governments use them to calculate planning scenarios to evaluate options to comply with TMDL regulations. The CBP uses the BMP efficiency in CAST to evaluate the effectiveness of various combinations of BMPs. The watershed model estimates nonpoint source nutrient and sediment loads by first estimating Bay average per acre loading rates for different land uses (Figure 10). Average loads are adjusted based on nutrient inputs from atmospheric deposition and fertilizer, manure and biosolid applications within a defined land segment of the watershed. This load is then multiplied by the number of acres of each landuse to generate a potential exported load (Stephenson et al. 2018). Within the model, BMPs reduce nutrient and sediment loads exported from the land segment as a percent reduction (or in some cases as an input prevented , e.g. nutrient management) in the potential exported load. The CBP typically assigns a single efficiency estimate for nitrogen, phosphorus, and sediment to each defined BMP. Land to Water factors add spatial variation in nutrient transmission by making adjustments to physical conditions (e.g. soil and geomorphic conditions) within the land segment. Together these factors produce total load estimates exported to the stream and river network. Attenuation factors are applied to land segment export loads to estimate the quantity of nutrients and sediment reaching the Bay (Figure 10).

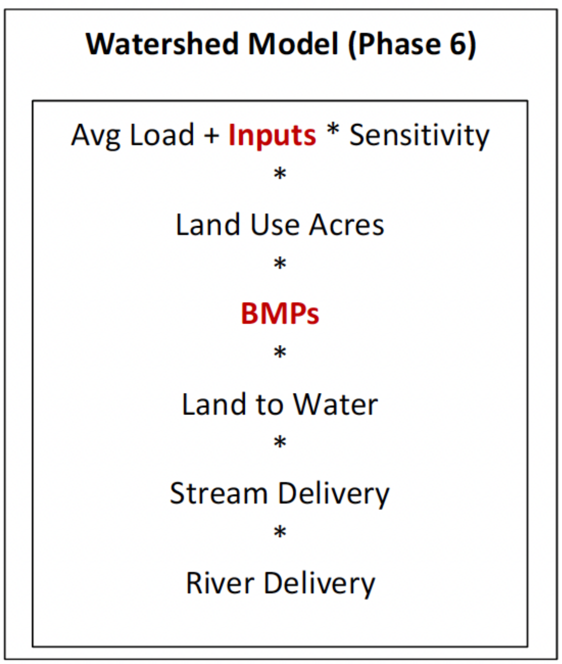


Figure 10. Conceptual framework of the CAST watershed model detailing how BMPs are accounted for in the Phase 6 Watershed Model (adapted from Stephenson et al. 2018).

Synthesis Question 1. How do climate change and variability affect nutrient/sediment cycling in the watershed?

To define how climate change affects nutrient and sediment cycling we evaluated published literature reviews, syntheses, and meta-analyses of nutrient and sediment yield, export or processing. We also include the impacts of climate change on hydrology, as changes to the hydrologic response impact BMP performance. As the most comprehensive database of scientific journal articles, selected the Web of Science and used searched for articles by topic using the following terms: " TS=((watershed simulation* OR hydrologic* model* OR biophysical model* OR process*based model* OR watershed model) AND (climate change OR climate variability OR climate uncertainty OR global warming OR temperature change OR precipitation changel) AND (nitrogen OR phosphorus OR sediment OR nonpoint source pollution OR water quality) AND (Chesapeake Bay))". Each article was screened for the following inclusion criteria according to the abstract and full text if needed: 1. Geographical relevance to the Chesapeake Bay Watershed, 2. Relevance to nonpoint source pollution loading or mitigation efforts under climate change, and 3. Relevance to climate change impacts on hydrologic response. The search yielded 92 results, 12 of which were determined to meet inclusion criteria and 14 of which were deemed supplementary.

Extracted data included: locational context (geographical location, land use, watershed size), climate scenarios used, climate models used, downscaling technique, watershed model used, spatial and temporal scale, and outputs/metrics (e.g., forecast N/P/sediment loads, model skill, rate change in some biogeochemical process). Extracted data from these studies was used to assess the relationships between study attributes and variability/uncertainty in climate predictions and N, P, and/or sediment cycling or export. Data quality were evaluated by assessing methodological rigor.

Brief Description of the (12) studies included in Synthesis Question 1

Chesapeake Bay Program, Chesapeake Bay: A description of the model used for the Chesapeake Bay Program climate change analysis is given above in this document, and in Shenk et al. (2021). For the climate change analysis, Shenk et al. (2021) made changes to both CAST and the dynamic model. The dynamic model was run with the long term trend in precipitation and temperature change extrapolated out to 2025, and with projected precipitation and temperature input data from an ensemble of 31 CMIP5 climate models after 2050 to predict changes in hydrology and sediment. CAST uses these changes to predict changes in nitrogen and phosphorus loads delivered to large rivers. While the CBP ran multiple RCPs, the results presented in the report are for RCP4.5. Then the dynamic model is used to temporally disaggregate the predictions of CAST, simulate the effects in large rivers, and pass loads to the estuarine model. They evaluated the impact of climate change on precipitation, temperature, precipitation intensity, ET, streamflow, and TN, TP, and sediment export. The CO_2 fertilization effect was incorporated with an empirical adjustment.

Alam et al. (2017), US: Using the The SPAtially Referenced Regression On Watershed attributes model (SPARROW) and downscaled precipitation and temperature outputs from 14 CMIP3 GCMs were used to assess the impacts on nitrogen yield in the conterminous US. They use two CMIP3 scenarios A2, and B1 for the periods 2030, 2050, and 2090.

Giuffria et al. (2017) Difficult Run VA, 15 km2:Using the SWMM model and NARCCAP A2 Scenario data for the 2045–2068, they assessed the impact of climate change (precipitation, temperature) on the costs of meeting various water quality goals.

Hawkins (2015), Chesapeake Bay: Using a rainfall runoff model and CMIP5 RCP2.6 and RCP8.5 scenarios, Hawkins (2015) assessed climate change impacts on precipitation, temperature, and the hydrologic response of the watershed, including ET, runoff, and soil moisture.

Lee et al. (2017), Two coastal plain CB watersheds, 220 & 290 km2: Using the SWAT model and CMIP3 A1B, A1, and B1 scenarios for the 2085-2091 period were used to evaluate the impact of climate change on precipitation, temperature, ET, streamflow, soil moisture, and NO_3 export. They considered the CO_2 fertilization effect on ET.

Lee et al. (2018), Two coastal plain CB watersheds, 220 & 290 km2: Using the SWAT model and CMIP5 RCP8.5 scenario for the 2083-2098 periods they evaluated the impact of climate change on precipitation, temperature, ET, streamflow, soil moisture, and NO_3 export. They considered the CO_2 fertilization effect on ET.

Modi et al. (2021) Susquehanna Basin 71,000 km2: Using NOAH-MP and CMIP5 RCP4.5 and RCP8.5 scenarios for the 2021-2050 and 2069-2090- periods, assessed climate impacts on precipitation, temperature, ET, runoff, and soil moisture, and crop water use. They considered the CO_2 fertilization effect on ET.

Muhling et al. (2018) Susquehanna Basin 71,000 km2: Using a water balance model and CMIP5 RCP8.5 scenario for the 2050-2090 period they assessed the impact of climate change on precipitation, temperature, and streamflow.

Renkenberger et al. (2016), Choptank Sub-basin, 298 km2; Using SWAT and CMIP3 A1B, A2, B! Scenarios for the 2046-2064 and 2081-2100 periods, they evaluated the climate change impacts on precipitation, streamflow, and TN, TP and sediment export.

Seong and Sridhar (2017), Chesapeake Bay: Using the CBP Model Phase 5.3, and CMIP5 RCP4.5 and RCP8.5 scenarios for the 2020-2029, 2040-2069, and 2070-2099 periods they reported on climate impacts on precipitation, temperature, ET, and streamflow.

Wagena et al. (2018), Mahantango Creek Watershed, 7.3 km2: Using SWAT and NARCCAP A2 scenario data for the 2045-2068 period they assess climate change impacts on precipitation, precipitation intensity, temperature, ET, streamflow, soil moisture, soil temperature, and NO_3, dissolved P, TP, Sediment P, and sediment export.

Wagena and Easton (2018), Susquehanna Basin 71,000 km2; using SWAT and CMIP5 RCP2.6 and RCP8.5 for the 2041-2065 and 2075-2099 periods they assessed climate change effect on precipitation, precipitation intensity, temperature, ET, streamflow, soil moisture, surface runoff, and NO_3, TN, Dissolved P, TP and sediment export.

Greater detail about the specific methodologies (e.g., model initialization data, downscaling and bias correction methods, assumptions) can be found in the appendix, table A1.

Climate change in the watershed and tidal systems

For the assessment of climate change impacts in the Chesapeake watershed, the primary variables considered were precipitation volume, precipitation intensity, air temperature, and ET. Estimates of the influence of sea level rise and atmospheric CO_2 concentrations are also included where appropriate. Scenarios for climate change indicate that by the end of the 21st century the Bay region will experience significant changes in climate conditions, dependent on radiative forcing, including increases in precipitation of 3-10%, temperature 2-6C, and sea level 0.7-1.0m. These factors interact in complicated ways to influence watershed level processes like streamflow generations, soil moisture, ET, and nutrient and sediment cycling. We review each of these parameters and how they interact to influence BMP performance. The CBP report on climate change (Shenk et al. 2021) describes in detail how the partnership is currently incorporating the impacts of climate change to develop planning targets, and one is referred to this document for clarity on specifics. We use this report as a point of comparison.

Precipitation Volume

The delivery of freshwater, nutrients, and sediment to the Bay is mainly driven by the amount and intensity of precipitation in the watershed. Thus, Bay circulation and water quality strongly respond to changes in watershed precipitation. Climate predictions for the Mid-Atlantic suggest that average annual precipitation quantities will increase.

Table 3 presents the climate change and watershed specific variables from 12 studies conducted in the Chesapeake Bay watershed since the assessment made by Najjar et al. (2010). Most of the climate change studies (7) used climate change data from the most recent Coupled Model Intercomparison Project, CMIP5. Clear differences exist between results using the most recent CMIP5 data and those studies using the older CMIP3 data. For instance, most of the studies relying on CMIP3 data project substantially higher precipitation amounts (+15% to +40%) in the future than CMIP5 studies, which are generally constrained to +3% to +10%, with the notable exception of (Lee et al. 2018), who predicted a +21% increase in precipitation, although for RCP8.5 at the very end of the century (2083-2098). These differences notwithstanding, all but one study (Lee et al. 2017) showed increases in precipitation over the watershed (f). Estimates from studies using CMIP5 data for the mid century indicate increases in precipitation volume from +3.8% (Wagena and Easton 2018) to +7.4% (Modi et al. 2021) for RCP4.5 to as much as +5.2% (Seong and Sridhar 2017) to +8.5% (Modi et al. 2021) for RCP8.5 (Table 3). End of century estimates from CMIP5 show greater increases, from +5.1% (Seong and Sridhar 2017) to +9.3% (Modi et al. 2021) for RCP4.5, and +8.5% (Seong and Sridhar 2017) to +21% (Lee et al. 2018) for

RCP8.5. Estimates from CMIP3 data suggest considerably greater precipitation variability and range, from estimates of precipitation declines of −3% to −4% (Lee et al. 2017) to substantial increases of +15% to +43% (Alam et al. 2017).

In a recent analysis by of the Susquehanna River basin, (Modi et al. 2021), employing CMIP5 MACAv2-METDATA, a statistically downscaled and bias-corrected weather model using constructed analogs, saw an increase in precipitation across both RCP4.5 and RCP8.5 and time periods (Figure 11 a & b) shows the average monthly change and inter-model variation in the precipitation (%), and 2 m air temperature [K] respectively across the six selected GCMs. Figure 11 a) depicts the monthly precipitation change and inter-model variation. Precipitation increased by 9% and 10% in RCP4.5 and RCP8.5 scenarios in the 2061-2090 period as compared to the historical period (1976-2005). Interestingly, a consistent increase of 7.5% in precipitation was observed across all models for RCP4.5 in the 2021-2050 period, whereas there was greater uncertainty of ±20 mm/month among the RCP 8.5 model scenarios with an overall mean change of 6% in the 2021-2050 period. A larger mean difference was observed during the winter and spring seasons while greater variation was observed during the summer and fall seasons for both RCP4.5 and RCP8.5. Likewise, a lower inter-model variation of ±5 mm/month was observed during the historical period for the winter and spring seasons as compared to the higher inter-model variation during the future period for the summer and fall seasons. A consistent increase was observed in the Appalachian Plateau and Valley region across all GCM's and scenarios except in the RCP 8.5 scenario during the 2021-2050 period, which was due to a decrease in precipitation in Pennsylvania and the lower portion of the Chesapeake Bay watershed.

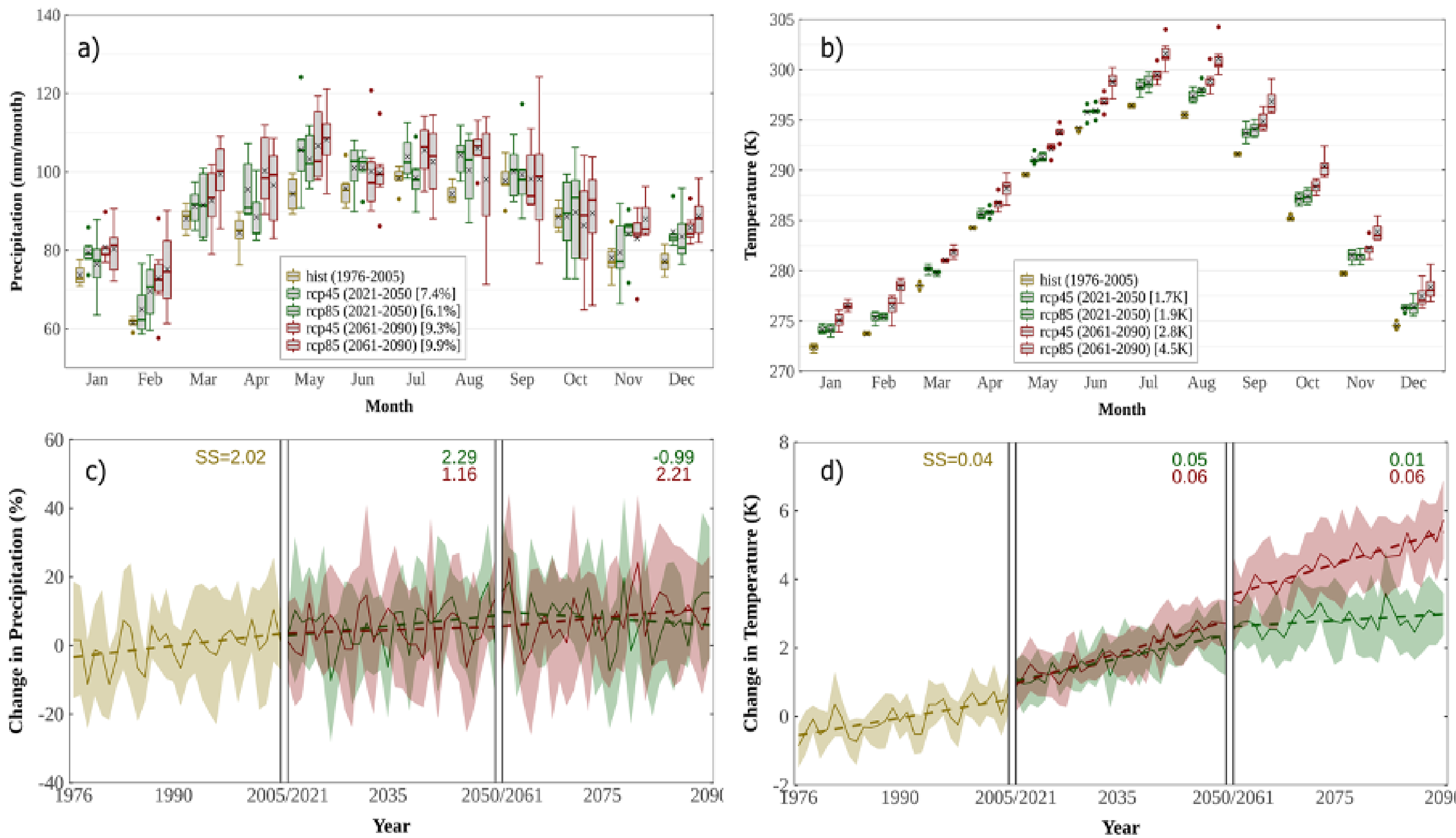


Figure 11. Box plots (a & b) representing the climatological monthly uncertainty and change for historical and future scenarios for precipitation, and 2m air temperature respectively for six GCM across the Susquehanna River basin. The values in box brackets indicate an overall change with respect to the mean of historical data from 1976-2005 and 'x' denotes the mean. Plots (c & d) show the annual change (mean and one standard deviation as ribbon) for historical and future scenarios. The change is with respect to the mean of historical data from 1976-2005. The values colored indicate the Sen's slope (SS) for the respective scenarios. The units for SS are mm/yr, and K/yr for c and d respectively (Modi et al. 2021).

Table 3. Studies reporting the impact of climate change on climatic drivers (precipitation, temperature, ET), hydrologic responses (streamflow, soil moisture, runoff), and other relevant parameters (precipitation intensity, CO_2 fertilization, soil temperature). The last column of the table contains information about the climate forcings and the watershed/hydrologic models used in the studies.

Source	**Precipitation**	**Temperature**	**Evapotranspiration**	**Streamflow**	**Soil Moisture**	**Other relevant information**	**Climate models/ scenario/ time span/ watershed model**
Shenk et al. 2021 CBP program estimates, entire CB watershed	<u>2025</u> +3.1% <u>2050 RCP4.5</u> +6.2%	<u>2025</u> +1.1C <u>2050 RCP4.5</u> +1.9C	<u>2025</u> +3.4% <u>2050 RCP4.5</u> +6.4%	<u>2025</u> +2.3% <u>2050 RCP4.5</u> +6.0%	Not reported	Observed change in 90th percentile precip intensity of +64.3%	Long-term trend to 2025 CMIP5 scenario RCP4.5 2050 Phase 6 WSM (HSPF)
Alam et al. 2017 Continental US, data from CB	<u>A2</u> 2030 +15% 2050 +20% 2090 +43% <u>B1</u> 2030 +14% 2050 +17% 2090 +39%	<u>A2</u> 2030 +1.3C 2050 +2.2C 2090 +4.0C <u>B1</u> 2030+1.3C 2050 +1.8C 2090 +3.0C	Not reported	Not reported	Not reported		CMIP3 Scenarios, A2, B1 Baseline 1992 Future 2030, 2050, 2090 SPARROW
Giufarra et al. 2017 Difficult Run VA, 15 km2	−14% to +30% Mean +6.7%	−1C to +2C Mean +1.3C	Not reported	Not reported	Not reported		NARCCAP A2 baseline 1989–2007 Future 2045–2068 SWIMM
Hawkins, 2015	RCP2.6 +5.2% RCP8.5	RCP2.6 +1.9C RCP8.5 +5.4C	<u>PET</u> RCP2.6 +11.3%	<u>Runoff</u> RCP2.6 +12.7%	RCP2.6 −2.7% RCP8.5 −11.2%		CMIP5 RCP2.6 & 8.5

CB	+15.2% Largest increase in winter and spring	Largest increase in summer fall	RCP8.5 +42.6% AET RCP2.6 +11.3% RCP8.5+32.2%	RCP8.5 −38.5%			Baseline 1950-1999 Future 2080-2099 Rainfall- runoff model
Lee et al. 2017 Two coastal plain CB watersheds, 220 & 290 km2	A1B -3.0% A2 -4.3% B1 -3.3% Largest declines in summer fall	A1B +3.4C A2 +4.1C B1 +2.1C Largest increases in summer fall	*A1B −31% A2 −34% B1 −27% Attributed to CO2 Fertilization effect	A1B +40% A2 +43% B1 +33%	Increases in soil moisture	CO2 effect increased the water balance and resulted in higher cover crop yields	CMIP3 A1B, A2, B1 Baseline 2001-2014 Future 2085-2091 SWAT
Lee et al. 2018 Two coastal plain CB watersheds, 220 & 290 km2	+11 to +21%	+2.9 to +5.0 C	−32% to -26%	+50% to +70%	Minimal increases in winter soil moisture, greater decreases in summer	CO_2 effect reduced ET	CMIP5 RCP8.5 Baseline 1999–2014 Future 2083–2098 SWAT
Modi et al. 2021 Susquehanna Basin 71,000 km2	RCP4.5 2021-2050 +7.4% 2069-2090 +9.3% RCP8.5 2021-2050 +6.1% 2069-2090 +9.9% Largest in winter and spring	RCP4.5 2021-2050 +1.8C 2069-2090 +2.7C RCP8.5 2021–2050 +2.4C 2069-2090 +4.1C Largest in summer fall	RCP4.5 2021-2050 −5% Corn, −4% Soy 2069-2090 −2% Corn, −2% Soy RCP8.5 2021-2050 −2% Corn, −2% Soy 2069-2090 −5% Corn, −6% Soy	RCP4.5 2021-2050 +2% Corn, +2% Soy 2069-2090 +6% Corn, +6% Soy RCP8.5 2021-2050 +5% Corn, +5% Soy 2069-2090 +14% Corn,	RCP4.5 2021-2050 +14% Corn, +13% Soy 2069-2090 +7% Corn, +7% Soy RCP8.5 2021-2050 +4% Corn, +2% Soy 2069-2090 +3% Corn, +3%	Evaluated CO2 fertilization effects, resulted in reduced crop water use −1% to − 18%	CMIP5 RCP4.5 & 8.5 Baseline 1976 to 2005 Future 2021–2050 2069-2090 NOAH-MP

				+13% Soy	Soy		
Muhling at al 2018 Susquehanna Basin 71,000 km2	+9%	+4.1C	Not reported	+11%	Not reported		CMIP5 RCP8.5 Baseline 1956-2005 Future 2050-2099
Renkenberger et al. 2016 Choptank Sub-basin, 298 km2	A1B +30% A2 +29% B1 +25% Do not provide break down by future periods	Not reported but used T from CMIP3 data	Not reported	*2046-2064 A1B +60% A2 +53% B1 +51% 2081-2100 A1B +75% A2 +86% B1 +52%	Not reported although water balance suggest substantial increase		CMIP3 A1B, A2, B1 Baseline 2001-2014 Future 2046-2064 2081-2100 SWAT
Seong and Sridhar 2017 CB	RCP4.5 2020-2029 +1.6% 2040-2069 +3.9% 2070-2099 +5.1% RCP8.5 2020-2029 +2.3% 2040-2069 +5.2% 2070-2099 +8.4%	RCP4.5 2020-2029 +1.7C 2040-2069 +2.5C 2070-2099 +3.0C RCP8.5 2020-2029 +1.8C 2040-2069 +2.7C 2070-2099 +3.2C	RCP4.5 2020-2029 +8.0% 2040-2069 +13.2% 2070-2099 +16.5% RCP8.5 2020-2029 +8.8% 2040-2069 +17.4% 2070-2099 +27.9%	RCP4.5 2020-2029 −10.5% 2040-2069 −11.1% 2070-2099 −12.4% RCP8.5 2020-2029 −11.1% 2040-2069 −13.5% 2070-2099 −21.8%	Not Reported		CMIP5 RCP4.5 & 8.5 Baseline 1970-1999 Future 2020-2029 2040-2069 2070-2099 Phase 5.3 WSM (HSPF)
Wagena et al. 2018 Mahantango Creek	−1.5 to +12.5% Mean +3.7%	Tmin +2.0 to +2.7C Tmean +2.5C	+2 to +17% Mean +7.5%	−16.1 to +34.3% Mean −0.7%	Increase on average	Precip intensity −3.8% to +11.4% mean	NARCCAP A2 Baseline

Watershed, 7.3 km2		Tmax +2.0 to +2.8C Tmean +2.5C				+5.1% Soil T +1.5 to +2.3C	1989–2007 Future 2045–2068 SWAT
Wagena and Easton 2018 Susquehanna Basin 71,000 km2	2041-2065 −5.1% to +14.2% Mean +3.8% 2075-2099 −3% to +10.7% Mean +6.5%	2041-2065 Tmin +1.3 to +2.0C Tmean +1.7C Tmax +1.7 to +2.3C Tmean +1.9C 2075-2099 Tmin +2.1 to +3.0C Tmean +2.7C Tmax +2.4 to +3.1C Tmean +2.8C	2041-2065 +3.1% to +14.2% Mean +4.7% 2075-2099 +2.9% to +15.7% Mean +7.4%	2041-2065 −10.1% to +14.8% Mean +4.2% 2075-2099 −3.9% to +16.6% Mean+ +6.7%	Increase in winter and spring, decrease in summer	Surface Runoff 2041-2065 −5.1 to +13.4% Mean +3.2% 2075-2099 −3.1 to +16.2% Mean +5.6% Precipitation Intensity 2041-2065 +6.5% 2075-2099 +10.1%	CMIP5 RCP2.6 & 8.5 (averaged) Baseline 1985-2011 Future 2041-2065 2075-2099 SWAT

Temporal precipitation variability was discussed in several of the studies in Table 3. Most studies agree that precipitation amounts are likely to increase in the winter and spring (Hawkins 2015; Lee et al. 2017; Modi et al. 2021; Shenk et al. 2021; Wagena et al. 2018), while summer fall precipitation levels are projected to decrease (Hawkins, 2015; Lee et al., 2017; Wagena et al., 2018). Winter and spring precipitation increases are as high as +25% (Giuffria et al. 2017; Modi et al. 2021), with a central tendency among studies using CMIP5 of +15% (Hawkins 2015; Lee et al. 2017; Wagena et al. 2018). Spatial variability in precipitation is also expected, with the northern region of the Bay watershed expected to experience greater precipitation in the near term, than the southern region, however, towards the latter part of the century, these projections are reversed, with the southern region seeing greater precipitation increases (Hawkins 2015; Shenk et al. 2021).

Consensus on Precipitation Volume: Significant increase in mean annual precipitation (Figure 12), with greater increases towards the end of the century for scenarios with greater CO2 levels (e.g., RCP8.5). Largest increases for the winter and spring period. Supported by high agreement and robust evidence among studies.

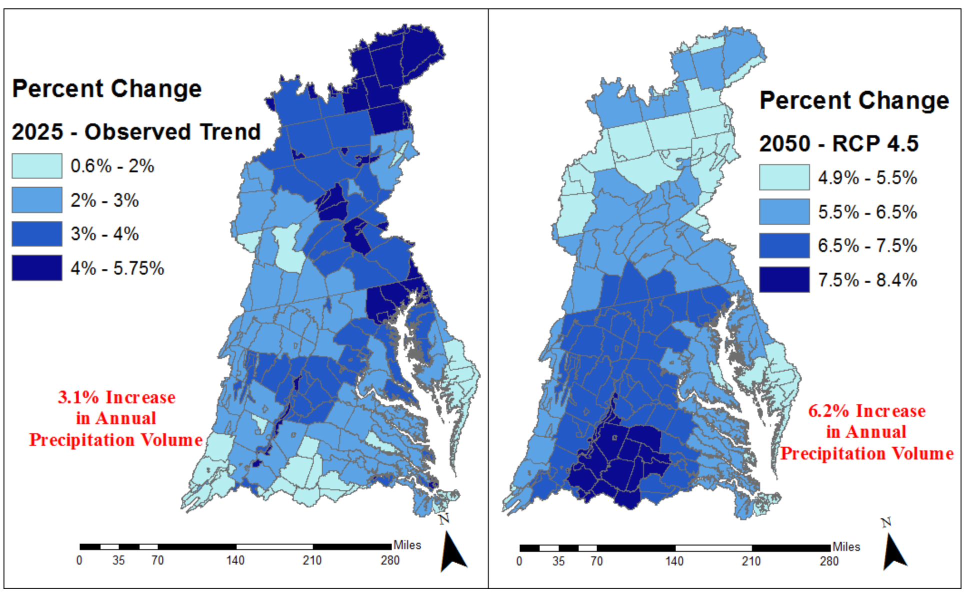


Figure 12. Estimated annual percent change in precipitation volume of counties within the Chesapeake Bay Watershed for climate projections of 2025 (left) and 2050 (right). (Shenk et al. 2021).

Precipitation Intensity

The frequency of high intensity precipitation events has increased substantially over the past decade with the greatest increases seen in the most extreme events (i.e., days with a total of at least 5.5 cm of rainfall) (Miro et al. 2021). Projections of future climate show that these extreme precipitation events will increase further in the coming decades. By the mid-21st century, the region "could experience a doubling of annual extreme precipitation events over 5-6 cm compared to historical averages (Fischbach et al. 2019). Many BMPs and most stormwater infrastructure are designed and managed around historic rainfall intensities and durations, so called intensity duration frequency (IDF) curves. IDF curves represent the relationship between rainfall intensity or depth, the duration of a rainfall event, and a measure of frequency, representing the average time between rainfall occurrences. Recently Miro et al. (2021) evaluated and modified IDF curves for the Chesapeake Bay region in an effort to incorporate the impact of climate change on rainfall intensity into BMP and stormwater design. IDF change factors (representing the proportional change between historic IDF curves and IDF curves expected with a changing climate) ranged from just over 1.05, to 1.5. This indicates that rainfall IDF curves used in BMP and stormwater design and management should be increased by 1.05 to 1.5, depending on location, return period, duration, and RCP. Figure 13 (from Miro et al. 2021) shows IDF change factors developed for the Chesapeake Bay region. Use of climate change modified precipitation products in BMP design and management is critical because much of BMP function is related to how much runoff or stormwater the BMP is designed to assimilate and treat. BMPs designed to historic precipitation records are prone to failure, or at the very least, reduced treatment efficiency (Wood 2021). Many agricultural or natural sector BMPs also rely on IDF curves and assumptions in their design.

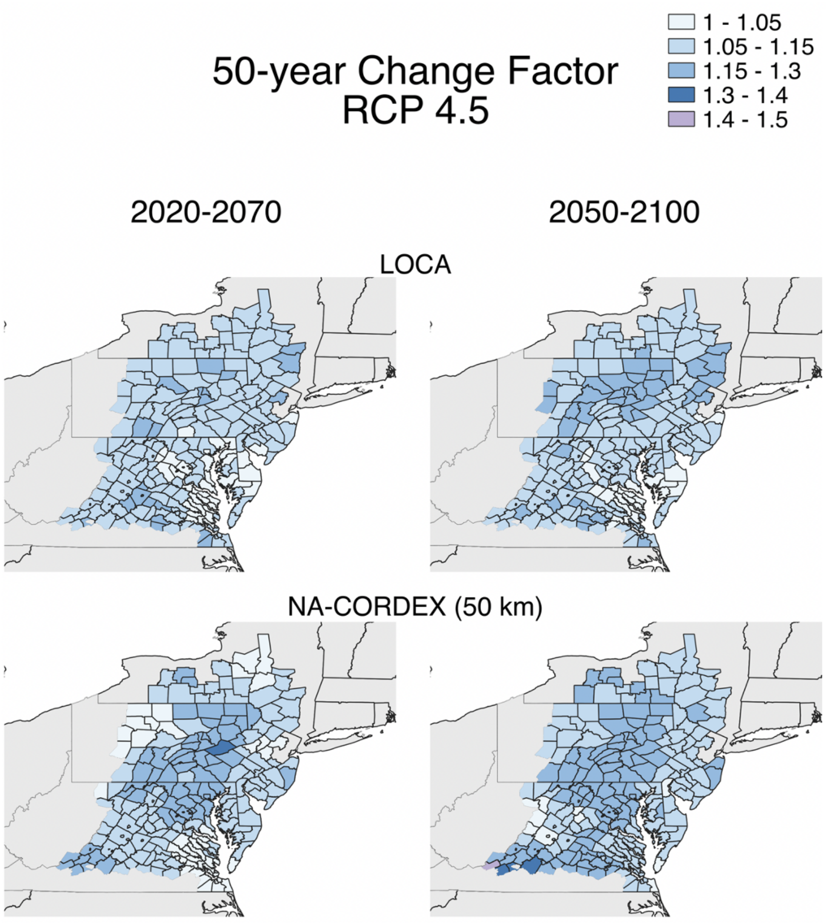


Figure 13. County-Level Change Factors for the Chesapeake Bay watershed Projected by the Ensemble Median of All GCMs in Each Dataset for Both Future Periods Under RCP4.5 (from (Miro et al. 2021). LOCA simulations are driven using Localized Constructed Analog climate data; NA-CORDEX simulations are driven using North American Coordinated Regional Downscaling Experiment climate data

Indeed several studies in Table 3 also suggest substantially greater rainfall intensity under future climates. Perhaps the most interesting and concerning from a BMP performance perspective (particularly for stormwater retention type BMPs) is the dramatic increase in observed precipitation intensity of the most intense storms by Shenk et al. (2021), who observed a 64.3 % increase in the 90th percentile and greater precipitation intensity. Several other studies noted precipitation intensity changes, from +5.1% (across all storm sizes) by Wagena et al. (2018) and +6.5% to +10.1 (across all storm sizes) by Wagena and Easton (2018) for mid and end of century, respectively. Hawkins (2015), Lee et al. (2018), and Modi et al. (2021) all report increased intensity as well, although do not provide numeric values.

Consensus on Precipitation Intensity: Substantially greater precipitation intensity, particularly for the most intense storms. Supported by high agreement and robust evidence among studies.

Air Temperature

The CBP climate change program (Shenk et al. 2021) projects mean annual temperature increases of +1.1C by 2025, and +1.9C by 2050, although there is significant variability in the location of those changes, with northern regions experiencing significantly higher temperatures (up to +1.2C by 2025, and +2.2C by 2050, for the Susquehanna river basin, Figure 14). Indeed, several other studies, particularly those employing CMIP5 projections, show similar temperature increases; for RCP4.5, over the Susquehanna river basin, (Wagena and Easton 2018) estimate mean annual temperature increases of +1.8C (2041-2065) and +2.7C (2075-2099), while Wagena et al. (2018) report a +2.5C (2045-2068) increase in mean annual temperature using the NARCCAP A2 data. Seong and Sridhar (2017) report consistent increase in mean annual temperature; for RCP4.5 +1.7C (2020-2029), +2.5C (2040-2069) , and +3.0C (2070-2099), for RCP8.5 +1.8C (2020-2029), +2.7C (2040-2069) , and +3.2C (2070-2099). Muhling et al. (2018) using RCP8.5 report the potential of a +4.1C increase for 2050-2099 (Table 3). Most other studies (Hawkins 2015; Lee et al. 2018; Modi et al. 2021) report similar, and substantial increases in mean annual temperature, with RCP8.5 showing increases of of +4C to +5C by the end of the century, and RCP4.5 in the +1.7C to +2.5C for the end of century time period (Table 3). Studies employing CMIP3 data (Alam et al. 2017; Giuffria et al. 2017; Lee et al. 2017) project temperature changes not terribly dissimilar to CMIP5 projections, in the +2.0C to +4.0C range, depending on time period and concentration pathay.

Also of interest is how the minimum and maximum temperatures change. Several studies reported that maximum temperatures are expected to increase proportionally more than minimum temperatures, although both minimum and maximum temperatures change substantially. Wagena and Easton (2018) also show minimum temperatures to increase +1.3C to +2.0C, and +2.1 to +3.0C for the mid-century and end-century, respectively while maximum temperatures increase +1.7C to +2.3C and +2.4 to +3.1C for the mid-century and end-century, respectively (Table 3).

Temporally, several studies report proportionally greater increases in minimum and maximum temperatures during the summer fall period, although there was greater variability in temperature changes during the winter and spring period. (Shenk et al. 2021) project the greatest increases in both minimum and maximum temperatures during the May-October period, with maximum temperatures increasing by +2.1C to +2.2C. Wagena and Easton (2018) report largest increase in maximum and minimum temperature occurring in April (+2.3C and +2.0C) for the 2041–2065 period, while during the 2075–2099 period both August and September (+3.1C and +3.0C) show the largest increases. Wagena et al. (2018) similarly report minimum temperature increases of +2.0C to +2.7C, and maximum temperature increases of +2.0C to+2.8C. Hawkins (2015), Lee et al. (2017, 2018) (Figure 15), and Modi et al. (2021) also report the largest increases in temperature during the summer fall period.

Consensus on Air Temperature: Large increases in mean annual temperature, with the greatest increases in the summer and fall. Almost all studies show a consistently increasing trend in temperatures towards the end of the century. Temperature increases are greater for more northern watershed regions. Supported by high agreement and robust evidence among studies.

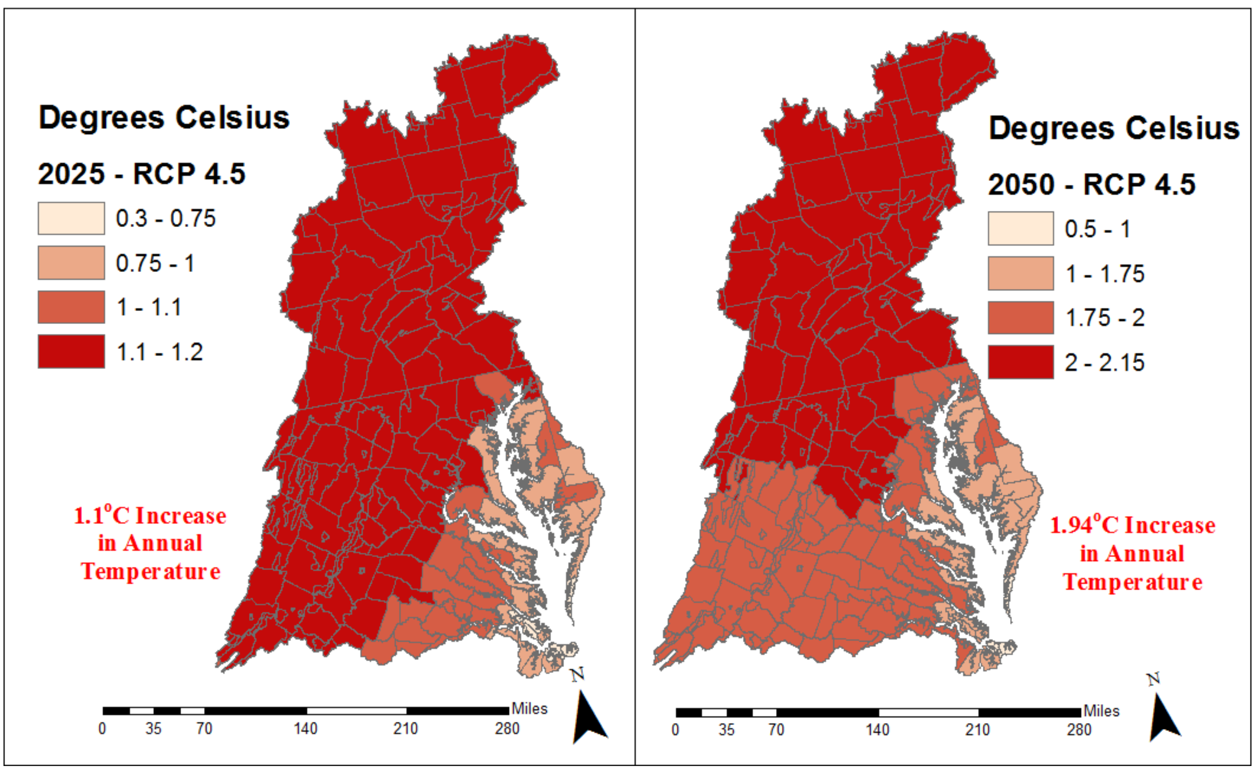


Figure 14: Estimated annual degrees Celsius difference in temperature for counties within the Chesapeake Bay Watershed for climate projections of 2025 (left) and 2050 (right) for RCP4.5. From Shenk et al. (2021)

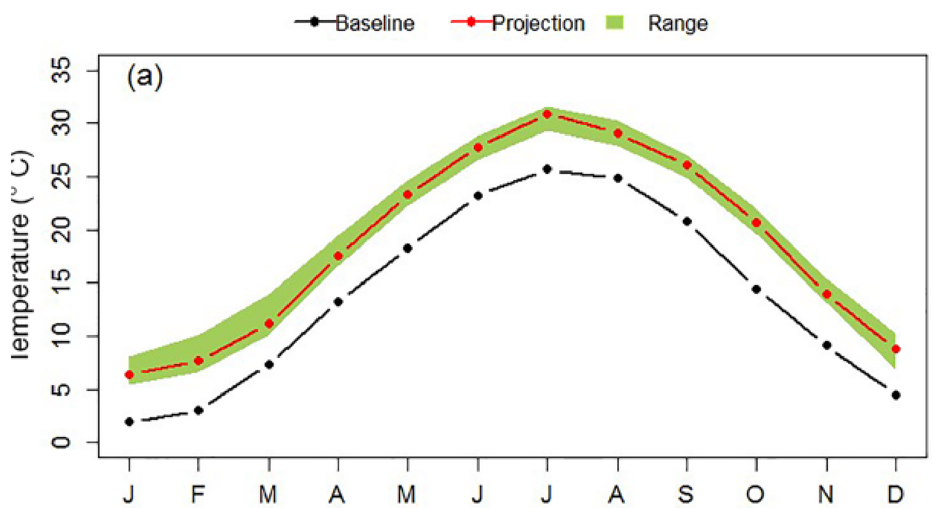


Figure 15: Monthly average mean temperature 2001-2014 (baseline) and 2085-2098 (future) CMIP5 GCMs under RCP8.5. From Lee et al. (2018)

Evapotranspiration (ET)

Estimates of changes to ET vary widely, depending upon radiative forcing scenario, time period, and most critically whether CO_2 fertilization was considered. Whether the studies report ET as potential ET (PET) or actual ET (AET) is also important, as several studies focus primarily on changes to PET, while others report changes to AET. This is significant because AET is limited by the availability of water (soil moisture), while PET is not. With respect to ET, the CO_2 fertilization effect describes the change in leaf level transpiration due to elevated atmospheric carbon concentrations. Occurring primarily in C3 plant species, elevated CO_2 levels increase plant photosynthetic efficiency, ultimately suppress stomatal conductance, thereby decreasing the water loss and the evaporative flux (Modi et al. 2021).

The CBP (Shenk et al. 2021) estimates that PET over the basin will increase by +3.4% for 2025, and +6.4% for 2050 Table 3, Figure 16. However, when the CO_2 effect is considered (numbers are unreported), their results indicate a reduction in AET, resulting in an increase in streamflow, although the increase in precipitation is noted as the dominant factor influencing streamflow. (Seong and Sridhar 2017), using RCP4.5 and RCP8.5 scenarios and (Hawkins 2015) using the RCP2.6 & RCP8.5 scenarios report much greater changes to PET, with (Seong and Sridhar 2017) estimating increases of +8.0% (RCP4.5 for 2020-2029) to +16.5% (RCP4.5 for 2070-2099) and +8.8% (RCP8.5 2020-2029) to +27.9% (RCP8.5 2070-2099), while (Hawkins 2015) report PET increases +11.9% for RCP2.6 and + 42.6% for RCP8.5, for the 2080-2099 period. (Hawkins 2015) report changes to AET that are slightly smaller, +11.3% for RCP2.6 and +32.2% for RCP8.5, with the difference between PET and AET due primarily to reduced soil moisture during the summer months constraining AET. Wagena et al., (2018) and Wagena & Easton, (2018) estimate much smaller increases to PET, +7.5% for Wagena et al., (2018) for the 2045-2068 period, and +4.6% from Wagena & Easton, (2018), for the 2041-2065 period and +7.4% for the 2075-2099 period.

Studies that incorporate the CO_2 effect all report reductions in AET. Lee et al. (2017) studied climate sensitivity scenarios and reported that the RCP8.5 CO_2 concentration towards the end of century resulted in a -27% (CMIP3 B1 scenario) to -34% (A2 scenario) reduction in AET due to lowered plant stomatal conductance. Reduced AET increased soil moisture as well as cover crop yields. Notably, the authors state that the standard version of the SWAT model they employed uses some questionable simplifying assumptions, such as constant maximum leaf area index (LA) and constant response to CO_2 for all plant species (C3 vs C4), which are known to exaggerate the reduction in AET. Lee et al. (2018), using the same model (SWAT) but updated CMIP5 RCP8.5 scenarios, report similar AET reductions of -26 % to -32% for the 2083-2099 period resulting in both increased soil moisture and streamflow. Modi et al. (2021) also report decreases in AET due to increased CO_2 concentrations, although the decreases were more modest; both corn and soy crops experience AET reductions in the -2% to -6% range (Table 3). Further, Modi et al. (2021) note that increased CO_2 concentrations increase crop water use efficiency, resulting in reduced water consumption for both corn and soy crops in the Chesapeake Bay watershed.

Consensus on ET: Potential ET is very likely to increase due to greater temperatures. While the CO_2 effect is real, and possibly significant, it is unclear if it will ultimately result in reduced AET at a quantifiable level. How AET changes depends on many other factors including temperature, plant type (C3 vs C4), soil type, soil nutrient content, and soil moisture. Supported by low agreement but robust evidence among studies.

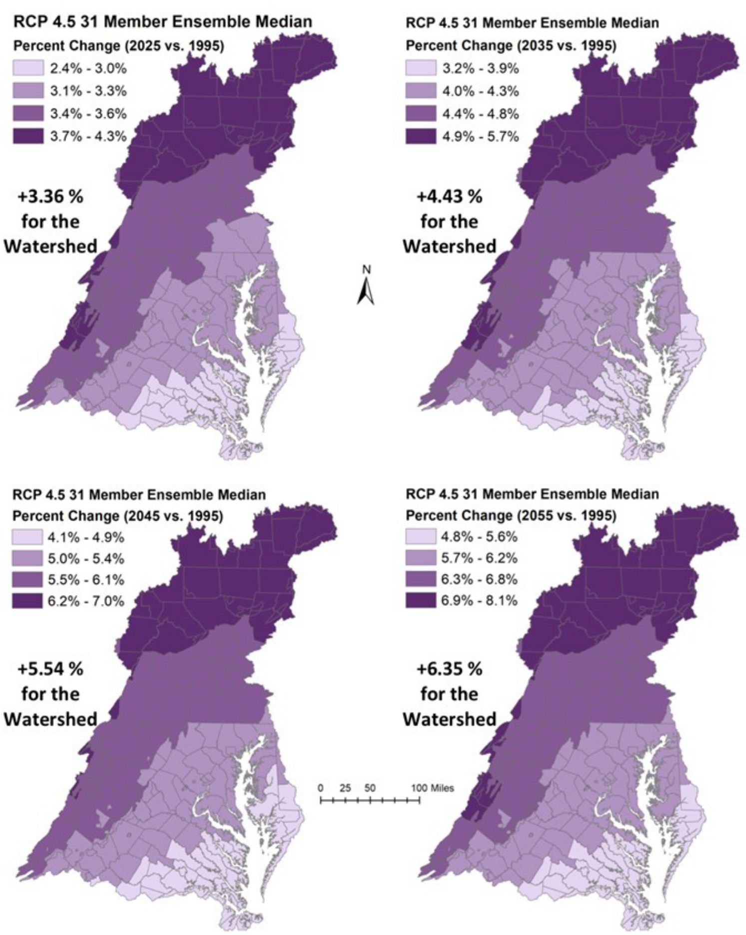


Figure 16. Estimated average annual change in potential ET (as percent change) for the land segments (counties) in the Chesapeake Bay watershed are shown for 2025 (top-left), 2035 (top-right), 2045 (bottom-left) and 2055 (bottom-right). The change in potential ET with respect to 1995 are based on a Hargreaves-Samani Method and 31-member ensemble median temperature change of downscaled Global Climate Models for RCPs4.5 scenario. From Shenk et al. (2021).

Other Climate Factors

Atmospheric CO_2 Concentrations

As discussed above, inclusion of atmospheric CO_2 concentrations can have (profound) impacts on plant growth, ET, and as a result soil moisture, streamflow, and ultimately nutrient and sediment export. Projections for global mean atmospheric CO_2 concentration over the next 80 years vary widely, depending on which RCP is assumed (Figure 7). However, it is virtually certain that CO_2 levels will continue to increase throughout the 21st century. Increases in CO_2 have many consequences for watershed and estuarine function, irrespective of precipitation and temperature changes, including estuary/ocean acidification and in plant growth/water use via ET (Kimball and Idso 1983). Increased atmospheric CO_2 levels can enhance plant productivity/growth by increasing photosynthetic efficiency, which suppresses leaf-level transpiration, ultimately reducing plant water use (Kimball and Idso 1983; Vanuytrecht et al. 2012). This CO_2 fertilization effect could have varying effects on water quality and BMP performance; for instance enhanced plant growth/yield results in greater plant biomass, and as a result enhanced nutrient uptake, yet improved water use efficiency of the plants results in less water uptake, and therefore the potential for increased nutrient uptake is diminished (Vanuytrecht et al. 2012) and increased soil moisture, both of which may ultimately result in reduced performance of BMPs that rely on plant growth/assimilation as a mode of action. With increasing precipitation and rising temperatures, plant productivity and water availability are likely to be uncertain as it is dependent on multiple factors, including soil properties, crop type, the interaction between land surface processes, water management strategies, and atmospheric CO_2 levels (Bhatt and Hossain 2019). For instance, climate change projections show risk of both too much and too little water (depending on season), as well as increasing heat stress, which could offset the potential positive effect of CO_2 fertilization on plants (Wolfe et al. 2018).

Sea Level Rise

There is observed acceleration in the rate of global average sea level rise in recent decades. The Chesapeake Bay area is one of the areas where there is accelerated relative sea level rise, Figure 17, accompanied with land subsidence (Parris et al. 2012). Projecting from a global mean sea level rise prediction, (Boesch et al. 2013) estimated, Maryland's relative sea level rise from +0.3 m to +0.7m by 2050 and +0.7m to +1.7m by 2100 relative to global mean sea level by the National Research Council. Wang et al. (2017) reported a mixed response to nutrient retention, due to a +0.5m sea level rise by 2050. Increased temperatures resulted in increased summer chlorophyll-a and as a result increased hypoxic volume. However, sea level rise in the lower bay and increased freshwater inputs in the upper bay counteracted the increase in chlorophyll-a in those regions, reducing the hypoxic volume However, Wang et al. (2017)caution that increasing watershed nutrient load of 5% to 10% offsets the reduction in hypoxic volume gained due to sea level rise.

Relative Sea Level Rise Scenarios for Annapolis from Hall et al. (2016) and Sweet et al. (2017)

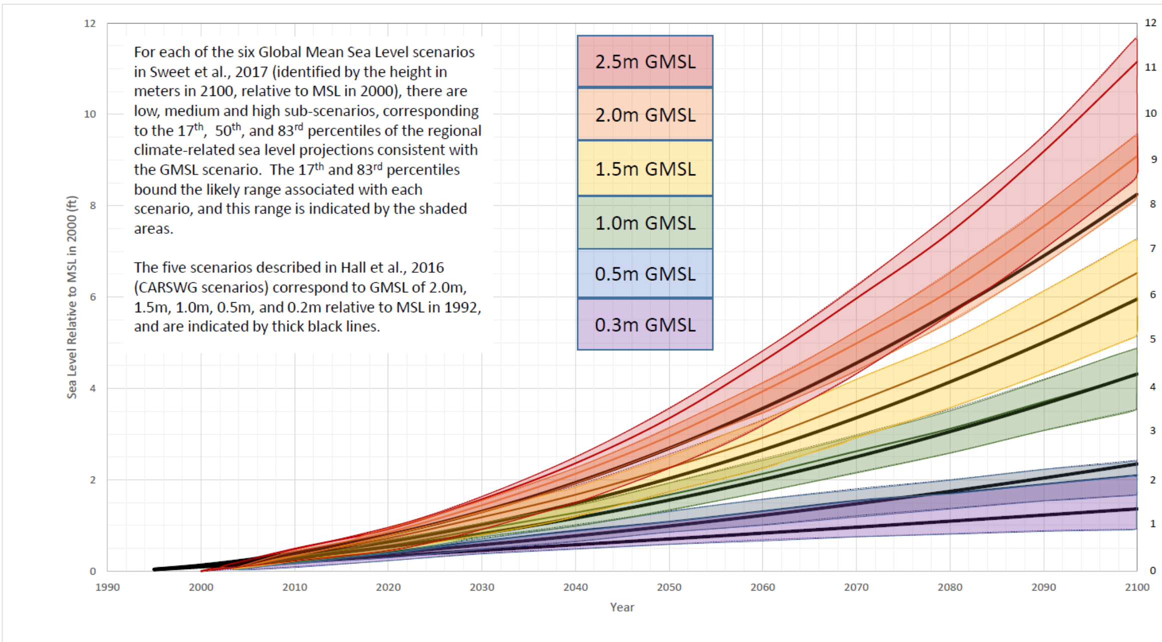


Figure 17. Relative Sea level rise scenarios for Annapolis MD. From (Sweet et al. 2017).

Watershed Response to Climate Change

Streamflow

Streamflow serves as a signal of climate change drivers on the watershed, integrating the effect of precipitation and temperature, and their impact on ET and the overall water budget. All of the studies meeting the inclusion criterion for the review are model based assessments of the impact of climate change on streamflow, therefore not only is there uncertainty introduced by the climate model (CMIP3 vs CMIP5, radiative forcing scenario), there is also considerable uncertainty that results from the choice of biophysical (watershed) model. In the section that follows one should keep in mind that the studies discussed here employ many different biophysical model structures, from empirical (Hawkins 2015); Alam et al. 2017) to more process based (Modi et al. 2021; Shenk et al. 2021), and therefore may produce results with varying level of uncertainty.

Estimates from the CBP (Shenk et al. 2021) show that the RCP4.5 integrated scenarios resulted in increased streamflow across the Chesapeake Bay watershed; for 2025 streamflow increased +2.3% and by +6.0% for 2050 (Table 3). They note these changes are consistent with climate change sensitivities where the rainfall change (rather than changes in temperature and CO_2) dominated the watershed response. Several other studies report changes to streamflow of similar magnitude. In a small 7.3 km^2 Mahantango Creek watershed Wagena et al. (2018) report essentially no change to streamflow (-0.7%) for the 2045-2068 period, due to increases in precipitation being countered by increases in ET. For the Susquehanna River basin, Wagena and Easton (2018) project modest increases to streamflow, +4.7% for 2041-2065 and +6.7% for

2075-2099. Modi et al. (2021), also working in the Susquehanna, report similar, modest, increases in flow (reported as total runoff, surface runoff + vadose zone percolation) of +2% to +6% (for RCP4.5 in 2021-2050 and 2069-2090, respectively), increases were somewhat higher under RCP8.5, +5% to +14% in 2021-2050 and 2069-2090, respectively. Several other studies also employed RCP8.5, but predicted substantially greater changes to streamflow. Hawkins (2015) showed a substantial decrease in late century (2080-2099) steamflow of -38%, although RCP2.6 changes were more modest (+12.7%). Again, the balance between precipitation and ET tended to control the streamflow response; here changes to ET appear to be the controlling factor behind the change to streamflow (Table 3, Hawkins 2015). On the Chesapeake Bay coastal plain, (Lee et al. 2018), using RCP8.5 for the 2080-2098 period, predict large streamflow increases, +50 to +70% due to concomitant increases in precipitation (+11% to +21%) and decreases in ET (-32% to -26%) from the impact of elevated CO_2. Conversely, Seong and Sridhar (2017) predict substantial reductions in streamflow for RCP8.5, -11.1% (2021-2029), -13.3% (2040-2069), and -12.8% (2070-2099), RCP4.5 results suggest slightly smaller reductions (-12.4% to -10.5%), with increases to ET significantly greater than increases to precipitation (+8% to +27.9% for ET vs +1.6% to +8.4% for precipitation).

Studies using CMIP3 climate scenarios all reported substantial increases in streamflow (+33% to +86%). For instance, Lee et al. (2017), on the coastal plain, reported significant streamflow increases; +40% (A1B), +43% (A2), and +33% (B1) for the 2085-2091 period. They attributed the increase in streamflow to the suppression of ET from increased atmospheric CO_2. While Renkenberger et al. (2016), in the Choptank watershed, show increases of +60% (A1B), +53% (A2), and +51% (B1) for the 2024-2064 period, to as high as +86% (A2 scenario for the 2081-2100 period (Table 3).

Seasonally, results from Shenk et al. (2021) suggest modest increases in winter streamflow (+4% to +6%) for the near term (2025) scenario, but substantial increases in 2050 scenario winter streamflow (+11% to +16%). Spring through fall showed smaller increases to slight decreases in streamflow. Wagena et al. (2018) state that through an increase in precipitation and temperature, there will be substantial increases in winter/spring flow (10.6 ± 12.3%), and conversely, decreases in summer flow (−29.1 ± 24.6%). However, the mean annual change in streamflow was very small (Wagena et al. 2018). Similarly, Hayhoe et al. (2007), reported higher high flows and lower low flows suggesting that climate change is likely to redistribute streamflow in the Eastern US. Further, Hayhoe et al. (2007) discuss a shift in the timing of spring high flows, occurring up to 2 weeks earlier in the spring, as well as earlier occurrence of low flows. Finally, Hawkins (2015) also predicted greater runoff during the winter months coupled with lower summer flows.

Consensus on Streamflow: Projections of streamflows response to climate change vary widely from -38% to +86%. Studies that simulated the impact of CO_2 fertilization on plant growth and ET tended to show modest to potentially large increases in streamflow, while studies not simulating the CO_2 effect varied tremendously in their projections of streamflow. However, the central tendency of streamflow estimates for the studies reviewed indicates moderate increases in streamflow, on the order of +5% to +15%, at least in the near term. Supported by medium agreement and robust evidence among studies.

Soil Moisture

Estimates of the effects of climate change on soil moisture are, similar to streamflow, a good integrator of climate impacts, particularly on ET. From the hydrologic water balance point of view the reported changes in streamflow and ET can be indicative of changes to soil moisture levels in the CBW. At monthly time scales variabilities are to be expected between the winter and summer roughly correlating with the variability of seasonal temperature and precipitation. Spatial variability in soil properties, infiltration capacity, drainage condition, topography and land use also results in varying degree of soil moisture changes in response to changes in climate. Similar to streamflow, most of the estimates of the impact of climate change on soil moisture in the Chesapeake Bay watershed are model based. Therefore, one needs to again consider the added uncertainty that comes with model on model applications. Unfortunately few studies reported quantitative estimates of climate change impacts on soil moisture, although most do report qualitative changes. Only two studies (Hawkins 2015; Modi et al. 2021) provide numeric estimates of the changes in soil moisture under climate change.

Modi et al. (2021), investigating changes in corn and soy crop water use predicted increased soil moisture due to increased precipitation and reduced ET in the Susquehanna river basin, using six CMIP5 GCMs under RCPs 4.5 and 8.5 Table 3. They reported, increased Pe (effective precipitation stored as soil moisture in crop root zone) levels and reduced ET (due to efficient photosynthesis with CO_2 fertilization), resulting in increased soil moisture, +14% for corn and +13% for soy (2021-2050) and +7% for both crops (2069- 2090) under RCP4.5 Figure 18. Under RCP8.5, both crops are predicted to still have higher soil moisture, although less than under RCP4.5, +4% for corn and +2% for soy (2021-2050) and +3% for both crops (2069- 2090). The increases in soil moisture were roughly inversely proportional to the decreases in ET Table 3. Conversely, Hawkins (2015), using RCP2.6 and RCP8.5 for the 2080-2099 period project decreases in soil moisture, -2.6% for RCP2.6, and -11.2% for RCP8.5. However, discrepancies in the components of Hawkins (2015) water balance, for instance increases in surface runoff concomitant with decreases in soil moisture, make reconciling the changes difficult.

Of the other studies, four reported increases in average annual soil moisture (Lee et al. 2017, 2018; Wagena et al. 2018; Wagena and Easton 2018). Several studies (Lee et al. 2017; Wagena and Easton 2018) note substantial (although not quantitatively reported) increases in the winter and spring soil moisture, and decreases during the summer months.

Consensus on Soil Moisture: Given the often substantial increases in precipitation and the potential decreases in ET due to increased CO_2, it seems likely that soil moisture will increase, particularly during the winter and spring, although several studies indicated increases during the summer months as well. Supported by medium agreement and medium evidence among studies.

These results corroborate findings by earlier studies in the region, some of which are discussed in Najjar et al. (2010). For instance, Hayhoe et al. (2007) , Rob et al. (2000), and Lu et al. (2015) all predicted increases in seasonal streamflow variability with decreased flow during the summer due to increased ET (driven by higher temperatures) and increased flow in the winter and spring due to increased winter precipitation and reduced snowpack.

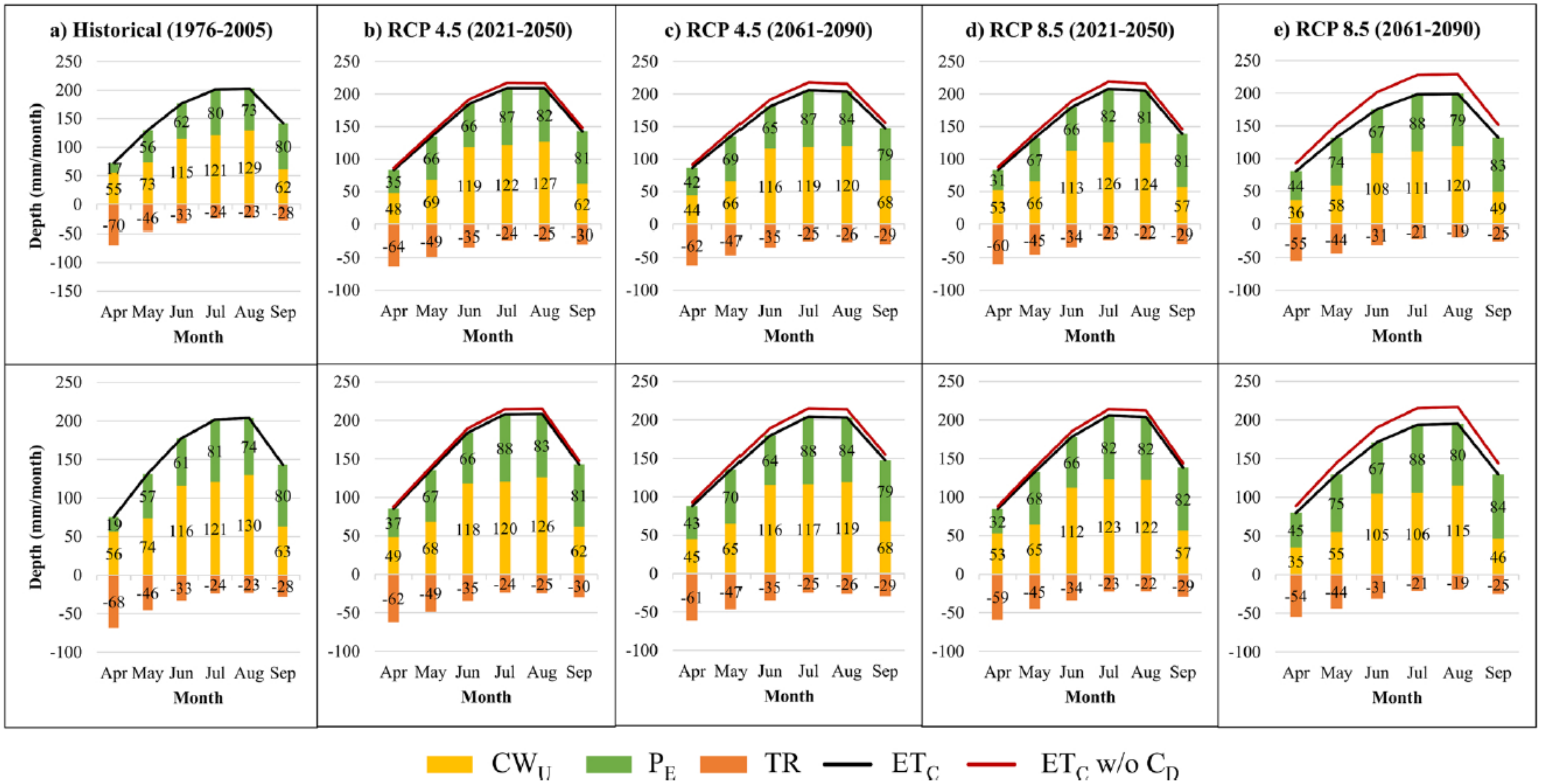


Figure 18. Water balance comparison of historical and two future periods, for RCP4.5 and RCP8.5 (from Modi et al. 2021). CW_u =crop water use, P_E = effective precipitation, TR=total runoff, ET_C = ET with CO_2 effect, ET_C w/o C_D = ET with no CO_2 effect. The top and bottom plots represent corn and soybeans, respectively.

Table 4. Studies reporting on climatic drivers on impacts on nutrient and sediment cycling and export, and the primary climate factors influencing the response..

Source	Nitrogen	Phosphorus	Sediment	Primary Climate Factors	Other
Shenk et al. 2021 CMIP5	2025 +2.4% 2050 RCP4.5 +8.3%	2025 +3.1% 2050 RCP4.5 +15.3%	2025 +3.3% 2050 RCP4.5 +16.2%	Increased water balance from greater precipitation volume (N) and intensity (P & Sediment)	
Alam et al. 2017 CMIP3	N Yield A2 2030 −3.6% 2050 −4.4% 2090 −13.9% B1 2030 −3.4% 2050 −4.8% 2090 −9.0%	Not reported	Not reported	N decrease from greater denitrification driven by increased temperatures	
Lee et al. 2017 CMIP3	NO3 A1B +28% to +43% A2 +27% to +42% B1 +23% to +35%	Not reported	Not reported	N increase from greater precipitation volumen	Biomass of cover crops A1B +7% to +24% A2 +37% to +58% B1 +37% to +43%
Lee et al. 2018 CMIP5	NO3 +56% to +66% Summer export −27% to −20.2%	Not reported	Not reported	N increase from greater precipitation volume and increased N mineralization from increased temperatures	Increases in yield with CO2 effects. Increased N mineralization +23% to +27%
Renkenberger et al. 2016 CMIP3	TN 2046-2064 A1B +61% A2 +57% B1 +56%	TP 2046-2064 A1B +49% A2 +47% B1 +43%	2046-2064 A1B +86% A2 +74% B1 +63% 2081-2100	Increased water balance from greater precipitation volume (N) and intensity (P & Sediment)	CSAs occupying 11% to 21% of the watershed area contribute 31% to 45% of constituents

	2081-2100 A1B +89% A2 +72% B1 +52%	2081-2100 A1B +62% A2 +74% B1 +49%	A1B +132% A2 +121% B1 +81%		
Wagena et al. 2018 NARCCAP	NO3 0% to +18.9% Mean +6.5% Winter export +24% to +29.5% Summer export −26.1% to +14.2%	DP −1.7 to +55.9% Mean +16.6% winter and spring +20 to +30% TP −0.2% to +43.2%, Mean +10.8% Sed P −4.5% to +35.8%, Mean +6.7% winter and spring +25.7% to +78.2%	−4.5 to +35.8%, Mean 6.7% winter and spring +8.7% to +56.2%	N increase from greater precipitation volume and increased N mineralization from increased temperatures. DP mineralization decreases from increased soil moisture (precipitation). TP & Sediment increase from higher precipitation intensity.	Increases in nitrification of 0% to +14%, Mean +6% , winter and spring +16.4%. Reduction in GHG emissions P mineralization decline −4.6% to −23.1% Mean −11.8%
Wagena and Easton 2018 CMIP5	NO3 2041-2065 −31.2% to +12.3%% Mean −9.2% 2075-2099 −29.4% to −6.5% Mean −14.7% TN 2041-2065 +4.7% to +13.3%% Mean +8.9% 2075-2099 +5.2% to +17.3% Mean +11.6%	DP 2041-2065 −27.2% to +4.3% Mean −16.4% 2075-2099 −27.1% to −1.9% Mean −11.8% TP 2041-2065 −14.7% to +5.6% Mean −4.5% 2075-2099 −10.9% to +6.4% Mean −2.1%	2041-2065 +6.8% to +59.6% Mean +25.9% 2075-2099 +17.6% to +71.2% Mean +28.7%	NO3 decline from increased denitrification. TN increases from greater precipitation volume. P & Sediment increases from greater precipitation volume & intensity.	
Xu et al. 2019	TN −2.9%	Not reported	Not reported		NARCCAP A2 Baseline 1989–2007 Future 2045–2068

Nutrient and Sediment Cycling/Export

Fewer studies in the Bay watershed report on alterations to nutrient and sediment cycling and export resulting from climate change. Eight model based studies were included in the synthesis (refer to Table 3). As with the hydrologic response of the watershed, results from the literature suggest a wide range of potential changes, both to processes influencing nutrient and sediment cycling, such as denitrification or phosphorus mineralization (Wagena et al. 2018), and to waterhead yield/export. In many cases the alterations to nutrient and sediment cycling and yield is proportional to the changes in precipitation occurring over the watershed. As discussed previously, increases in precipitation are particularly pronounced during the winter/spring periods, with slight declines during the summer, which may increase nitrogen (N), phosphorus (P) and sediment export from watersheds (Chang et al. 2001; Cousino et al. 2015). Drier conditions in the summer and fall also have been shown to increase the buildup of soil nutrients that can subsequently be flushed from the system when wet conditions return (Kaushal et al. 2008; Wetz and Yoskowitz 2013). Temperature (and ET) can also affect changes to nutrient and sediment yield/export, by altering how nutrients in particular, are cycled in the biomass, soil, and groundwater. Understanding these changes is critical to planning and implementing resilient BMPs.

Nitrogen

All eight studies included in the review reported on changes to nitrogen cycling and or export as summarized in Table 4. Estimates from the Bay program (Shenk et al. 2021) suggest modest increases in nitrogen (Total N) yield from the watershed; +2.4% for 2025, and +8.3% for 2050 for RCP4.5 (Table 4). Results from the sensitivity analysis (Shenk et al. 2021) suggest that changes to precipitation were the most significant factors resulting in increased delivery of nitrogen, while changes to temperature and its impact on ET were less significant, but resulted in decreased delivery of N. Integrated scenarios (combined temperature, precipitation, and CO_2 effect) show changes in N export to largely follow changes in streamflow; for 2025 flow increased +3.1% with an associated increase in N export of +2.4%,for 2050, flow increased +6.0% an, with an associated increase in N export of + 8.3%. Also similar to flow, the largest changes in N export tended to be seen during the November to May period, with increases as high as ~+17% (2050), summer N yield increases tended to be smaller (~+2% to +4% for 2050). Notably, Shenk et al. (2021) results suggest substantially greater N yields for more southern basins, including the James, Rappahannok, and Potomac, which all display N yield increases well above the watershed average (on the order of +12% to +15% increases for 2050).

Several other studies report changes to N export of similar magnitude Table 4. For instance Wagena et al. (2018) report an +6.5% increase in annual NO_3 export (2045-2068), with substantial winter and spring increases (+24% to +29.5%); summer changes N yields were variable, ranging from +14.2% increases, to -26.1% decreases, depending on the individual climate model. (Wagena et al. 2018) also show substantial increases in large event (Q90) nitrate (NO_3) export and a decrease in smaller event (Q10) NO_3 export, indicating substantially more variability than the historic record displayed. Peak NO_3 export timing does not change considerably, historically occurring in March, during snowmelt, late May, following fertilizer application and again in December following crop harvest, but winter export increases significantly, from 60 to 80 kg d−1 to 85–105 kg d−1. The historic summer/fall (June–November) NO_3 export is substantially reduced under future conditions, primarily a result of decreased streamflow from reduced runoff that result from drier summer soils, while the increase in winter/spring is due to greater runoff and increased nitrification from warmer wetter soils (Wagena et al. 2018). Xu et al. (2019), using data from Wagena et al. (2018), report a slight decrease in annual total N (TN) export, -2.9%, due warmer future temperatures decreasing streamflow and increasing denitrification, although they did not report on the seasonal timing of those changes.

Wagena and Easton (2018) report a decrease in NO_3 export, but an increase in TN export for the Susquehanna River basin using CMIP5 projections. Nitrate is expected to decrease by -9.2% for 2041-2065 and -14.7% for 2075-2099, while TN increases by +8.9% for 2041-2065 and +11.6% for 2075-2099 (Table 4). They report that the decrease in NO_3 is due to increased denitrification from warmer temperatures and higher soil moisture, while the increase in TN is driven primarily by a decrease in both mineralization and nitrification, particularly during the drier summer periods (Groffman et al. 2009b) allowing more soil TN build up.

(Alam et al. 2017), using SPARROW and CMIP3 climate data suggest slight decreases in annual TN yield for the Chesapeake Bay watershed. Decreases range from -3.4% for the 2030 periods B1 scenario to-13.9% for the 2090 periods A2 scenario Table 4. They suggest these changes are due to higher temperatures in the watershed lowering N yields because of greater denitrification (Schaefer and Alber 2007).

Results from the other studies in Table 4 (Lee et al. 2017, 2018; Renkenberger et al. 2016) show much greater changes to N yields. Lee et al. (2017) predict substantial increases in annual NO_3 yield using CMIP3 data for the 2085-2099 period; A1B scenario +28% to +43%, A1 scenario +27% to +42%, and B1 scenario +23% to +35%, depending on crop type (rye vs wheat vs barley) These responses are due to the much greater predicted streamflow under the future climate Table 4, and less so on any alterations to N cycling in the watershed. Lee et al. (2018) using CMIP5 data for the 2083-2098 period show similarly large NO_3 yield increases, +56% to +66% for two adjacent coastal plain watersheds. They note substantial intra annual changes to NO_3 yields, with substantial summer increases (+35,6% to +62.5%), changes during the winter and spring were more variable, with one watershed exhibiting a -9.5% decrease and the other showing a +1.6% increase. Both Lee et al. (2017 and 2018) considered the CO_2 effect in their analyses, concluding that increased water yield, caused by elevated CO_2 concentrations reducing ET anduced considerable increase in summertime nitrate yield. Further, Lee et al. (2018) suggest that the increase in NO_3 yield is also due to increased N mineralization of +23% to +27%, similar to Wagena et al. (2018). Renkenberger et al. (2016) also using CMIP3 data for the 2046-2064 and 2081-2100 periods also report very large changes to TN yields. They suggest that near term (2046-2064) TN yields my increase by +56% (B1 scenario) to +61% (A1B scenario), while late century TN yields are even more variable and potentially even larger (+52% for the B1 scenario to +89% for the A1B scenario).

Consensus on Nitrogen: Large changes to nitrogen cycling and export can be expected, although there is a great deal of uncertainty encompassing these predictions. The direction and magnitude of these changes depends on many factors (climate models and radiative forcing used, timing of precipitation and temperature changes, effect of elevated CO_2, biophysical model used, landscape management, etc), and how they interact. The consensus CMIP5 (model based) estimates suggest slight increases in N yield (NO_3 or TN) of approximately +3% to +10%, although there is variability around these estimates as well. Studies employing CMIP3 data contain considerably greater ranges of N yield, from increases of +89% to decreases of -13.9%. Most estimates tended to be driven primarily by changes in streamflow, as induced by precipitation and temperature effects, and not changes in internal (watershed) N cycling. Supported by medium agreement and medium evidence among studies.

Phosphorus

Only four systematic review studies in the Bay watershed report climate change impacts on phosphorus (P) cycling or yield (Table 4). Estimates from the Bay Program (Shenk et al. 2021) show moderate to substantial increases in phosphorus loading, with a +3.1% increase in 2025 and a +15.3% increase in 2050 for RCP4.5. Similar to N, P yield predictions tended to increase most substantially for the Potomac, James, and Rappahannok basins (~+22% to +30% for 2050). Also similar to flow and N, seasonal changes in P yield tended to follow changes in precipitation, with proportionally greater increases in P yield occuring in the winter period, on the order of +4% to +7% for 2025, and +15% to +19% for 2050, summer changes were minimal (<2%).

In the Susquehanna River basin, Wagena and Easton (2018) showed most climate models predicting a decrease in both TP and DP during both scenario periods (Table 4). The mean annual DP export decreased by +16.4% for the 2041–2065 period and +11.8% for the 2075–2099 period. Mean annual TP decreased by -4.5% for the 2041–2065 period and -2.1% for the 2041–2065 period. The decrease in DP was driven by decreased mineralization of fresh organic P in the soil, by +11.8% and +18.2% during 2041–2065 and 2075–2099 periods, respectively. This resulted in decreased DP (and as a result TP) export of +10.3% and +8.6% during 2041–2065 and 2075–2099, respectively. This was despite an increase in surface runoff and sediment export (Table 4).

In the small WE38 experimental watershed Wagena et al. (2018) predicted mean annual increases in both dissolved and total P, with DP increasing +16.6% and TP increasing +10.8% Table 4. Similar to Shenk et al. (2021), increases tended to be greatest in winter and spring, although Wagena et al. (2018) predictions are more variable (+20% to +30%). Similar to streamflow, there is considerable variability among the mean annual change predicted by the models for DP export (−1.7% to +55.9%) although they note substantial increases in high flow yields and decreases in lower flow yields. Further they note that the increased DP yields occur despite a decrease in soil P mineralization (the conversion of insoluble organic P to soluble inorganic P, dissolved P), due to a significant increase in surface runoff and sediment-bound P from increased storm intensity. In fact the P mineralization decline was quite significant (−4.6% to −23.1% with a mean of −11.8%), but was countered by increases in runoff + (+3% to+6%) Table 4. Wagena et al. (2018) also found that at the watershed scale sediment P increased a modest amount, +6.7% Table 4 but at the agricultural field scale that sediment bound P yield increased substantially, driven by large winter/spring increases. Mean annual increases ranged from +2.1% to +47.4%, with a model mean increase of +20.9%. Increases in the winter and spring range from +25.7% to +78.2%, while decreases are predicted during the summer fall (−6.0%). The increased peak winter and spring export was due to the combined effect of increased surface runoff, greater rainfall intensity, reduced snow cover, and spring tillage occurring simultaneously.

Using CMIP3 data Renkenberger et al. (2016) for the 2046-2064 and 2081-2100 periods report very large changes to TP yields. They suggest that near term (2046-2064) TP yields my increase by +43% (B1 scenario) to +49% (A1B scenario), while late century TP yields are even more variable and potentially even larger (+49% for the B1 scenario to +72% for the A2 scenario). These increases are due to similar increases in streamflow/runoff in the watershed (Choptank), which ranged from +51% to 86% (Table 4), and not a result of any identified changes to P cycling in the watershed.

Consensus on Phosphorus: Similar to nitrogen, phosphorus processing and export/yield predictions for a changing climate exhibit substantial variability, both in magnitude (-16.1% to +74%) and in timing. While there is variability in the annual P export predictions the central tendency of the studies included in Table 4 indicate modest annual changes (likely increases on the order of +3% to 15%) depending on time period and radiative forcing. Of the studies that reported intra annual changes to P export, all report substantial increases in winter and spring export, with most also predicting a decline in the summer. The most important factors controlling P export are precipitation intensity and precipitation volume (as expressed via streamflow), with temperature influencing P yields to a lesser extent. Supported by high agreement and medium evidence among studies.

Sediment

The Bay Program estimates of sediment export changes from climate change (Shenk et al. 2021) (Shenk et al. (2021), Table 4) are similar to changes predicted for sediment; a +3.3% increase for 2025, and a +16.2% increase for 2050 for RCP4.5. Based on climate sensitivity, these changes are driven primarily by increased precipitation intensity, followed by precipitation volume, with temperature having less of an impact on sediment production and transport. Shenk et al. (2021) note that although the differences in simulated flow are almost similar between their methodologies (distributing rainfall across equal intensity deciles vs using the observed intensity changes where there has been a 64.3% increase in the rainfall intensity in the highest decile >Q90%), the resulting changes in sediment delivery is quite significant. That is, there is much greater sediment delivery using the observed rainfall intensity changes, due to higher delivery of particulate matter with higher intensity events. Temporally, Shenk et al. (2021) indicate much greater increases in winter and spring period sediment delivery (~+5% to +20%) than in summer, but with substantial variability among the 31 climate models, with winter and spring delivery ranging from approximately -20% to +82% (Figure 19).

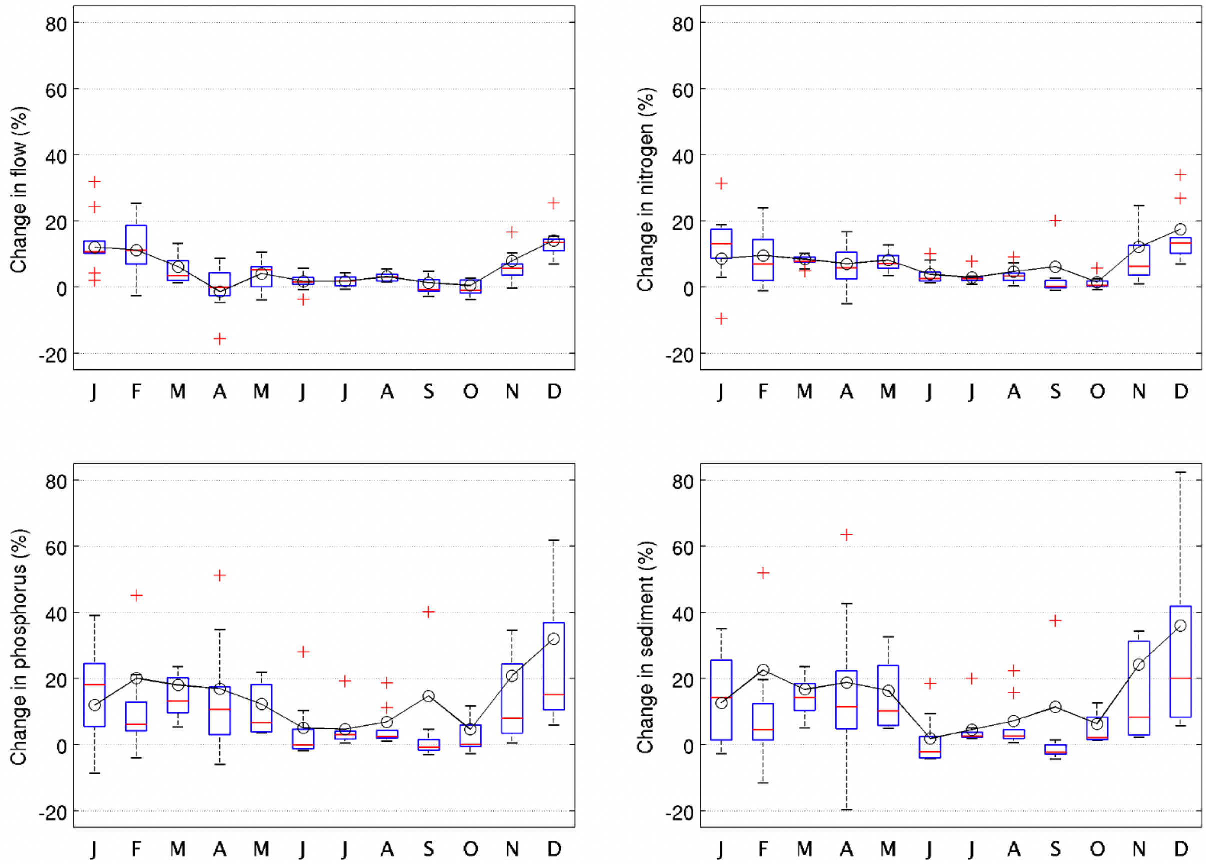


Figure 19. Chesapeake Bay Program estimates of changes in flow, nutrients, and sediment for the 2050 period, using CMIP5 RCP4.5 radiative forcing. Box and whiskers show interannual variability, whereas the solid lines show average annual change. From Shenk et al. (2021).

Only three review studies reported on changes to sediment delivery, Renkenberger et al. (2016), using CMIP3, Wagena et al. (2018), using NARCCAP, and Wagena and Easton (2018) using CMIP5. Wagena et al. (2018), in a small agricultural watershed, predicted watershed level sediment export increases of +6.7% (2045-2068), with considerable variability among the seven climate models used (-4.5% to +35.8%). They noted increases in Q90 (+17.1%) sediment export, with reductions in the Q10 metric. and that much of the annual increase is due to increased sediment export in the winter and spring period coinciding with tillage of the agricultural fields and reduced ground cover. Wagena et al. (2018) also looked at the potential climate change impacts at the agricultural field level (Figure 20). Sediment yield from the agricultural field in the watershed increased +8.0%. All seven climate models predicted substantial increases in sediment yield during the winter and spring (+6.6% to +43.5%). These increases were consistent with and of similar magnitude as the changes in surface runoff. They note that the increase in sediment-bound P is proportional to the increase in sediment yield.

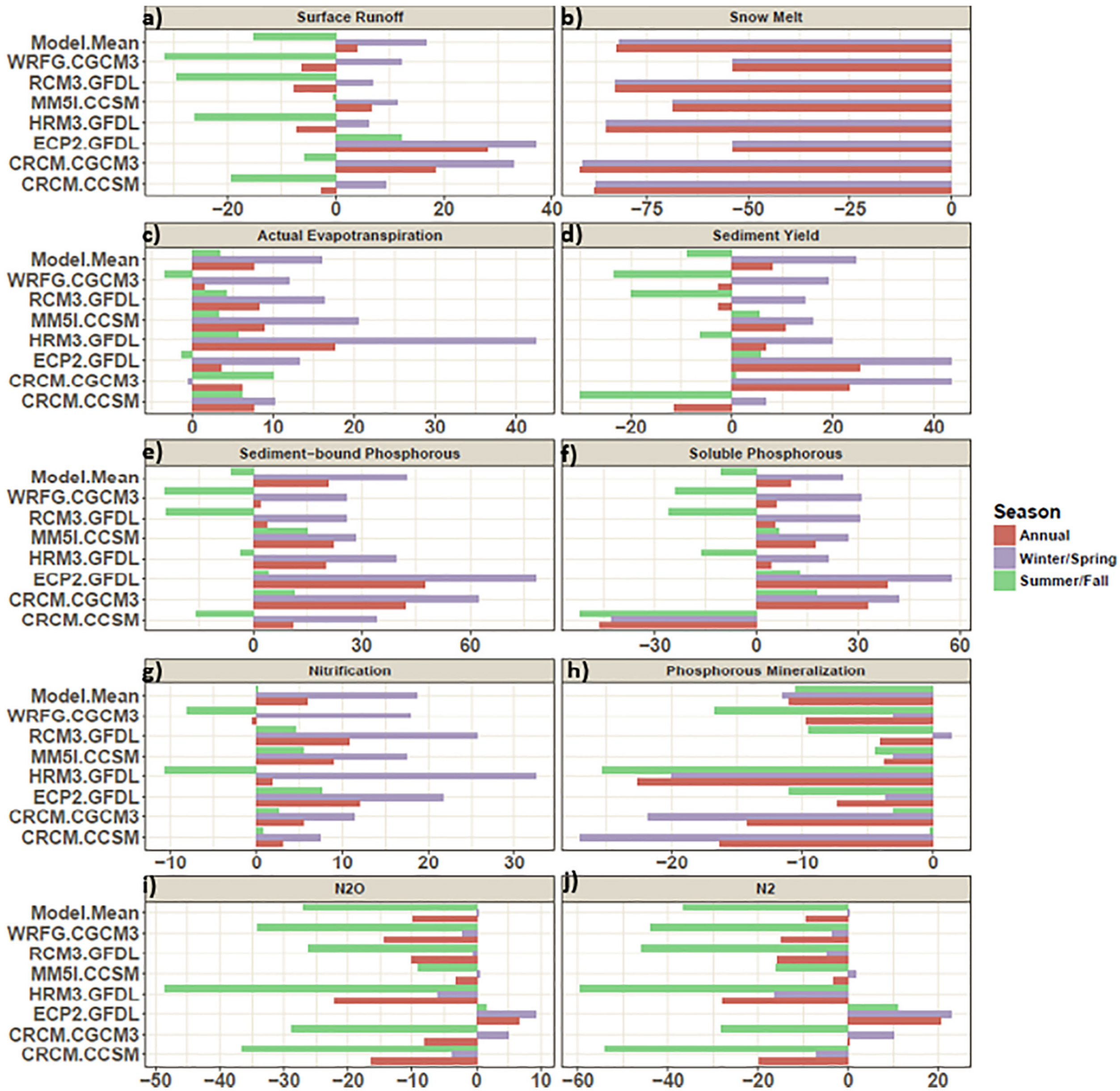


Figure 20. Annual and seasonal changes (%) for surface runoff (a), snowmelt (b), actual evapotranspiration (c), sediment yield (d), sediment-bound P export (e), dissolved P export (f), nitrification rate (g), phosphorus mineralization rate (h), N2O emission rate (i), and N_2 (j) emission rate averaged across agricultural HRUs for seven NARCCAP climate models relative to a historical scenario (1975–1998) for the future time period (2045–2068). From Wagena et al. (2018).

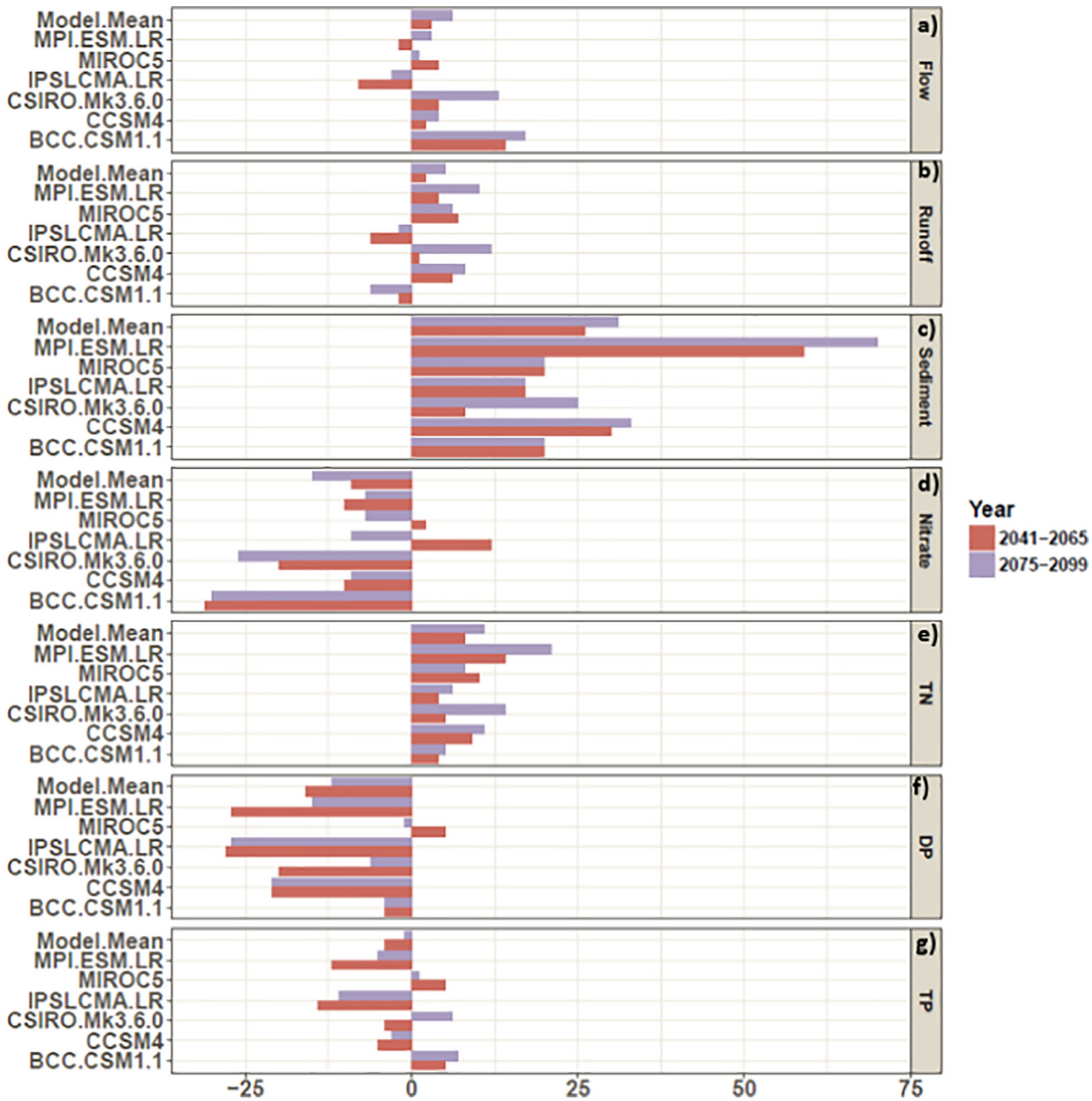


Figure 21. Percent change from the historical baseline for flow(a), runoff (b), sediment (c), nitrate (d), total nitrogen (e), dissolved phosphorus (f), and total phosphorus (g) for the six individual CMIP5 climate models, and two future climate periods. From Wagena and Easton (2018)

Wagena and Easton (2018), in the Susquehanna River basin, report increases of +25.9% (2041-2065) and +28.7% (2075-2099). The reported changes are substantially larger than the values reported by Shenk et al. (2021), or Wagena et al. (2018) in Table 3. However, in the Wagena et al. (2018) analysis all six climate models predicted, often substantial, increases in sediment delivery; +6.8% to +59.6% for 2014-2065 and +17.6% to +71.2% for 2075-2099, while individual climate forced model prediction from Shenk et al. (2021) and Wagena et al. (2018) were in less directional agreement (e.g. individual models produced both increases and decreases in sediment delivery (Figures 19, 20 & 21). Wagena and Easton (2018) determined that three primary factors are largely responsible for the substantial sediment increases; one is the timing of precipitation with increases occurring in the winter and spring period, when there is less ground cover, the second is greater precipitation intensity (+6.5% to +10.1%), and the third is an increase in surface runoff, which they report as +3.2% (2041-2065) and +5.6% (2075-2099).

Using CMIP3 climate data, Renkenberger et al. (2016), in the Choptank watershed, predict sediment delivery to increase by +63 % to +132%. The greatest increases are for the 2081-2100 period; +132% for A1B, +121% for A2, and +81% for B1 scenarios. Mid-century (2046-2064) increases in sediment delivery are more modest, but still substantially higher than other studies in the basin; +86% for A1B, +74% for A2, and +63% for B1 (Table 4). They suggest that increases in both the precipitation volume and precipitation intensity, primarily occurring in the winter and spring period, are responsible for the majority of the annual increase. Further they note that critical source areas (CSAs) of the watershed (areas characterized by disproportionately high sediment losses) are likely to expand in extent given climate change, stating that CSAs currently occupying 18% of the watershed area, generating 46% of sediment, will increases to between 37% to 45% of the area, generating 75% to 81% of the sediment.

Consensus on Sediment: All studies reporting sediment changes under a changing climate indicate increases in sediment yield. Although there was considerable variability among studies, those employing CMIP5 projections tended to suggest sediment increases on the order of +5% to +20%, with greater sediment yields towards the end of the century, and losses concentrated in the more intense storms. Precipitation intensity, followed by precipitation volume, and increased surface runoff were the most critical factors influencing increased sediment yield. Wagena et al. (2018), in a small agricultural watershed, predicted watershed level sediment export increases of +6.7% (2045-2068), with considerable variability among the seven climate models used (-4.5% to +35.8%). They noted increases in Q90 (+17.1%) sediment export, with reductions in the Q10 metric. and that much of the annual increase is due to increased sediment export in the winter and spring period coinciding with tillage of the agricultural fields and reduced ground cover. Wagena et al. (2018) also looked at the potential climate change impacts at the agricultural field level (Figure 20). Sediment yield from the agricultural field in the watershed increased +8.0%. All seven climate models predicted substantial increases in sediment yield during the winter and spring (+6.6% to +43.5%). These increases were consistent with and of similar magnitude as the changes in surface runoff. They note that the increase in sediment-bound P is proportional to the increase in sediment yield. Supported by medium agreement and limited evidence among studies.

Synthesis Question 2: How do climate change and variability affect BMP performance?

Evaluating how climate change may impact efforts to restore and protect the Chesapeake Bay poses challenges from the accumulation of uncertainty through future climate impacts on pollution generation, transport, BMP pollutant processing, and the ultimate response of the Bay ecosystem. Building on our previous discussion of climate impacts on hydrology nonpoint source pollution, here we examine the effects of climate change and variability on BMP performance. A simplified material balance for nutrient and sediment control BMPs (Figure 1) provides a conceptual framework for approaching this question and demonstrates the complexity of climate drivers affecting each component of the model.

Our goals are identifying which BMPs are likely to result in the best water quality outcomes under climate change and the uncertainties that will dominate the CBP's ability to predict nutrient delivery to the Bay. To this end, we begin with describing some key terms or concepts that were not covered in the previous section. We then describe our systematic search methodology to identify the pollution removal mechanisms and factors influencing BMP performance to answer the question: by what mechanisms can climate change and variability affect BMP nutrient and sediment removal efficiency? The complexities of addressing this question are illustrated with an application of the above conceptual model (Figure 1) to several BMPs, cover crops, stormwater infiltration practices, and tidal wetland restoration. We provide a summary of the published literature identified by our systematic search for each BMP, which provides a useful overview of the relative supporting research for each practice and some of the knowledge gaps. Expanding to a broader range of BMPs, we categorize practices according to their pollution reduction mechanisms and summarize the dominant factors controlling pollution reduction. By comparing the factors influencing BMP performance to the major climate impacts and uncertainties identified in question one, we address the mechanisms and unknowns of climate impacts. We discuss the current understanding of BMP performance uncertainty and risk of failure compared to the expected risks associated with future climates to answer the question: how does climate change uncertainty affect BMP performance variability? The susceptibility of BMPs to climate impacts is also evaluated in terms of a risk spectrum, ranging from diminished performance to complete failure of a BMP. Knowledge gaps and additional research needed to support robust landscape management are identified. We conclude with a discussion of opportunities for improved decision-making given future climate uncertainties, including recommendations for the Chesapeake Bay Program to feasibly fill some of the most glaring and urgent knowledge gaps.

Synthesis Question 2a. By what mechanisms can climate change and variability affect BMP nutrient and sediment removal efficiency?

To define BMP pollution reduction mechanisms and identify the dominant factors controlling BMP performance, we evaluated published literature reviews, syntheses, and meta-analyses of nutrient and sediment pollution reduction by urban and agricultural BMPs. As the most comprehensive database of scientific journal articles, selected the Web of Science and used searched for articles by topic using the following terms: "TS=((review OR meta-analysis OR meta analysis OR synthesis) AND (best management practices OR conservation practices) AND (removal OR efficiency OR performance) AND (nitrogen OR phosphorus OR sediment))". Results were updated weekly with an automated search for new publications.. Each article was screened for the following inclusion criteria according to the abstract and full text if needed: 1. reports agricultural or urban bmp performance in efficiency (% removal) or removal rate (mass/time), 2. combines data from multiple studies or multiple study sites, 3. pollution removal may be empirical and modeled (but the evidence of performance from empirical studies will be weighted more heavily), 4. addresses a widely used practice (as previously defined). The search yielded 412 results, 46 of which were determined to meet inclusion criteria and 302 of which were excluded. Extracted data included: locational context (geographical location, land use, watershed size), study characteristics (number of sites/studies, duration), BMP characteristics (pollutants addressed, measure of central tendency (mean and/or median, as available) and range of pollutant removal efficiencies (concentration or load reduction) or removal rates, performance variability, factors identified by the original authors as influencing BMP performance, and other ecosystem services provided), and major conclusions by the original authors. Data quality were evaluated by assessing methodological rigor; nearly all studies were determined to be of sufficient quality, but a few initially included studies were ultimately lower priority because they overly relied on modeling results (e.g., a review of (semi)mechanistic models of vegetated filter strips by Yu et al. 2019), or they were broader review papers that arbitrarily cited several articles for a given BMP rather than summarized findings from a systematic search (e.g. a review of new and major technologies for N and P reduction in agricultural runoff (Xia et al. 2020)).

Subsequent to the initial search, several BMPs based on habitat value and other ecosystem services were prioritized: living shorelines, tidal wetland restoration, oyster restoration, oyster aquaculture, and forest buffers. An additional search of was conducted in the Web of Science databases for articles published in 2000 or later producing 206 hits: TS=((climate change OR climate variability OR climate extremes OR climate uncertainty OR global warming OR future climate OR saltwater intrusion OR saltwater inundation OR acidification OR sea level rise OR resilience OR adaptation) AND (living shoreline OR veg* shoreline OR wetland restoration OR marsh restoration OR oyster restoration OR oyster aquaculture OR forest buffer OR nature-based OR green engineering OR green infrastructure OR natural infrastructure OR engineering with nature OR reef balls OR reef maker OR rock sill OR coir logs OR oyster castles OR wave abatement) AND (removal OR efficiency OR performance OR effect*) AND (nitrogen OR phosphorus OR sediment OR water quality OR nonpoint source pollution OR diffuse pollution) AND (tidal OR Chesapeake Bay OR estuar*) NOT (mangrove)) AND AD=(United States OR USA). Inclusion criteria were relaxed from the initial search given the lower availability of publications for some of these practices and their tendency to be assessed more broadly in terms of ecological function rather than by quantitative effects on N, P, and sediment. Therefore criterion one to derive data from multiple studies or sites was eliminated, and criterion two was expanded to include qualitative evaluation on pollutants, including addressing water quality impacts indirectly (e.g., change in denitrification potential rather than N load reduction or .

Forty-seven articles were determined to meet inclusion criteria, of which two duplicated the initial search, yielding 45 additional articles.

Table 5 -Table 8 summarize the study design and findings for the literature collected by these systematic searches. Studies are grouped by BMPs in separate tables by sector, Agriculture (Table 5), Natural or Cross-Sector (Table 6), and Urban (Table 7). We present large, cross-cutting reviews of a range of BMPs separately in Table 8 to emphasize their broadly applicable conclusions, which are discussed in more detail below.

We acknowledge several important limitations to our literature search methodology. Applying principles of a systematic review to address our broad research questions about climate impacts on BMP performance, we aimed to avoid bias in literature selection and drawing on a wide range of literature to build a mechanistic understanding of BMP function from published evidence rather than a priori knowledge. To balance the needs for comprehensive and efficient data collection and synthesis, we selected a 'review of reviews' approach, which focused on previous literature review, meta-analyses, and scientific syntheses on the topic of BMP performance. For some practices, more relevant and complete information would be obtained by focusing on field studies conducted within the Chesapeake Bay watershed rather than limiting investigation to higher-level synthesis studies. For example, the extensive meta-analysis of phosphorus fertilizer agronomic and environmental impacts by Chien et al. (2010) combines data from a wide variety of crops, fertilizer formulations and application methods, and geographic locations that drawing any quantitative conclusions is difficult. Relatedly, management practices that are more complex (as nutrient management involves many different components and decisions) or diverse (as cover crops involve hundreds of combinations of cover and crop species), appeared less likely to be represented in previous science syntheses captured by our search; we captured no reviews or meta-analyses of cover crops. Some BMPs, particularly nature-based approaches and ecological restoration produce such site-specific outcomes that systematic review methodologies are difficult to apply and first-order, individual studies would likely provide better evidence for addressing our research questions. Ultimately, the methodological decisions intended to produce a comprehensive overview of the literature may have limited our ability to synthesize published data for particular BMPs, introducing bias and limiting our conclusions. However, we provide a useful resource and starting point for future research focused on individual BMPs or elements of our research questions. Additionally, the abundance of literature on a particular BMP provides some insight into where research gaps exist, though the caveats of the 'review of reviews' approach and limitations of our particular search terms is acknowledged.

Table 5. Agriculture BMPs

BMP/Study	Description
Nutrient management	
Abalos et al. 2014	Meta-analysis of urease inhibitor and nitrification inhibitors
Chien et al. 2010	Review of agronomic and environmental effects of various forms of P fertilizer reinforcing the “4R’s” clearly lower the risk of P loss, but quantitative effects difficult to summarize given variety of crops, methods, and locations of studies.
Quemada et al. 2013	Review of 44 studies to assess four strategies to reduce nitrate leaching from irrigated cropland, including water and fertilizer management, cover crops and “fertilizer technology,” which included a total of 279 observations of nitrate leaching and 166 for crop yield. The authors found that adjusting water application reduced nitrate leaching by 80% on average without a loss in crop yield; improving fertilizer management reduced nitrate leaching by 40% on average.
Xia et al. 2017	Meta-analysis of 376 studies (with 1166 observations) to assess effects of seven N management practices on crop productivity, nitrous oxide emissions, and major reactive N losses with respect to major grain production in China (rice, wheat, corn). The seven specific practices (# observations) include: controlled-release N fertilizer (332); nitrification inhibitor (NI) (151); urease inhibitor (UI) (80); higher splitting frequency of fertilizer N application (241); lower basal N fertilizer (BF) proportion (92); deep placement of N fertilizer (38); and optimal N rate based on soil N test (232). The authors refer to the practices collectively as “knowledge-based N management,” which they found could increase grain yield while reducing various N losses.
Conservation tillage or no-till	
Blanco-Canqui and Lal 2009	A key paper for understanding the role of crop residue along with Ranaivoson et al. (2017). Review that focuses on soil and environmental benefits of crop residue, includes a thorough review of soil physical and chemical properties with respect to effects of residue removal. The authors synthesize information with a focus on the crop residue independent of tillage considerations. They offer a lot of generally useful insights. Among their conclusions, they find that based on the rapid response of soil organic matter and nutrient pools, that residue removal can be detrimental to future soil productivity and environmental concerns such as pollution from soil erosions and greenhouse gas emissions. They argue that unless threshold levels of residue are maintained alongside implementation of other BMPs such as cover crops,

	removal of residues will increase soil erosion, reduce soil organic carbon sequestration and nutrient pools, and eventually contribute to reduced crop production.
Blanco-Canqui and Wortmann 2020	Review of studies to assess the role and impact of occasional tillage within continuous no-till systems. They discuss some potential benefits or or other effects: as a general increase in sediment and sediment-bound nutrient losses, but a reduction of both pesticides and dissolved nutrients in runoff. Though the authors note there is limited data from the 30 reviewed studies regarding the length of useful time for occasional tillage and they suggest that the benefits are short-lived (<2 years) and occasional tillage is not a regular option for continuous no-till systems. They conclude there is little to no effect on greenhouse gas fluxes or long term carbon sequestration from occasional tillage.
Smith and Chalk 2020	Review of over 116 studies that used ^{15}N isotopic techniques to evaluate the effect of tillage and no-till cropping systems. The authors conclude that the reviewed studies were “surprisingly consistent” in showing relatively little impact of tillage on N mineralization, immobilization and N use efficiency. They found that N2 fixation was greater under no-till under two conditions: when mineral N was lower and plant available water was improved due to weed suppression.
Ranaivoson et al. 2017	Key paper for understanding role of crop residue for a range of agro-ecological functions, notably soil water infiltration or evaporation, water runoff, soil erosion, soil N or P, and others. The authors analyze data reported in the literature, compared to a bare soil no-till baseline, and present findings mostly based on residue amount (tons per hectare) but they also chart data when reported as residue coverage (CBP tillage practices include residue coverage percentages in their definitions). The data includes a wide range of crops, with an international scope that includes a wide range of climate conditions.
Cover crops	
Quemada et al. 2013	See under nutrient management above.
Bergtold et al. 2017	An “economic review” of cover crops but no specific discussion of nutrient or sediment reductions or processes
Bosch et al. 2014a; Schmidt et al. 2019; Wallace et al. 2017; Xu	Studies identified through 2(b) search and review, which include cover crops in their modeling studies.

et al. 2019	
Riparian forest buffers[1]	
Sweeney and Newbold 2014	Key paper. Reviews upland and in-stream benefits of buffers and considers significance of buffer width, suggesting that buffers of 30m or more offer the best protection of their assessed range of environmental benefits to the stream ecosystem.
Vegetated buffers or filter strips	
Zhang et al. 2010	Develops theoretical models of vegetated buffers' ability to remove N, P, sediment or pesticides; vegetation types discussed include trees, grass and mixed.
Liu et al. 2008	Review of 80 buffer experiments identifying dominant factors and optimization for sediment trapping.
AWMS	
BMP Expert Review Panel	Collection, storage, and transfer--recovery of animal waste so those nutrients can be applied as part of a NMP (or potentially subject to manure treatment technologies) rather than lost from landscape were at potentially high rates often from critical source areas (e.g., near streams). I see little opportunity for CC to impact AW collection/storage/transfer other than uncovered lagoon storage, which can be covered or enlarged to accommodate larger storm inputs. Climate change impacts come in at the NMP level (and presumably elevate nutrient export baseline in absence of AWMS + NMP): how does CC affect NUE? Fertilizer requirements and availability? Aside: manure analysis recommended but rarely used as part of NMP
Other	
Koelsch 2005	Case-study of CAFO BMPs finding voluntary BMPs including modified feeding programs could have a larger impact than mandatory BMPs like NMP or buffers.
Cristan et al. 2016	Review of forestry BMPs by geographic region of the US. Does not provide a numerical summary of pollution reduction efficiency.
Mondelaers et al. 2009	Meta-analysis of organic vs. conventional farming effects on N and P leaching.
Kubota et al. 2018	Effect of organic vs. conventional farming on nitrogen use efficiency.
Mack et al. 2019	BMPs for nurseries/greenhouses
Ross et al. 2016	Drainage water management

Lammerts van Bueren and Struik 2017	Review of crop breeding effects on nitrogen use efficiency.
Xia et al. 2020	Non-systematic review of N removal technologies, including "ecological ditches" and use of biochar.

[1] Riparian forest buffers listed here in the agriculture BMPs table due to extreme length of "natural" BMPs table; the CBP has multiple versions of forest buffer practices; the studies listed may relate to any of them, including urban forest buffers.

Table 6. Natural or cross-sector BMPs

Study	Description
Constructed wetlands or treatment wetlands	
Jahangir et al. 2016	A review that demonstrates even engineered systems like constructed wetlands exhibit inconsistent pollutant removal, varying based on the type of constructed wetland, climate, season, location and operations/maintenance. The authors note potential improvements to nutrient removal from mixed vegetation and greater retention times, but with the caveat that empirical evidence was limited at that time.
Brisson et al. 2020	Meta-analysis of treatment wetlands (28 studies) found significant but low effect of plant diversity on TN removal, marginal effect on TP and no effect on TSS; overall mixtures not more efficient than best monoculture for WQ, but since no difference better to use mixture for co-benefits.
O'Geen et al. 2010	Review of "constructed and restored wetlands" with a good overview of contributing processes for various pollutants' removal (including N, P, sediment, pesticides, dissolved organic matter, metals, pathogens). Conceptually they mostly discuss "constructed wetlands" as defined for CBP purposes. They generally highlight the importance of the same factors and processes as outlined by the 2016 and 2020 wetland BMP panels (landscape position and inflow, hydrology and retention time, previous site characteristics and history, among others).
Wetland restoration (nontidal)	
Ballantine and Schneider 2009	Not from initial search; cited by reviewed lit Looked at 30 restored palustrine depressional wetlands in NY state of varying age classes, concluding that some soil properties crucial for water quality take decades or longer to reach levels of natural reference wetlands.
Moreno-Mateos et al.	Key paper for overview of wetland functions, wetland restoration (both non-tidal and tidal). Meta analysis

2012	of 621 restored wetland (including 220 newly constructed) sites compared to 556 reference site function, globally. They conclude that even a century after restoration the biological/vegetative and biogeochemical functions are lower than reference sites. They suggest that large wetlands (>100 ha) or wetlands in warm climates recover more rapidly. Also, they conclude that riverine and tidal wetlands recover functions faster than depressional sites (greater hydrologic exchange).
Mason et al. 2016; Law et al. 2020	Wetland expert panels (2016 and 2020) were informed by both the above studies, among others.
Wetland restoration (tidal)	
Liu et al. 2021	Key paper. Meta-analysis to evaluate differences in accretion, elevation, and sediment deposition between natural and restored coastal wetlands globally. The authors conclude that restored coastal wetlands can trap more sediment and that the effectiveness of these restoration projects is primarily driven by sediment availability, not by wetland elevation, tidal range, local rates of sea level rise, and wave height. They suggest that these nature-based approaches can mitigate coastal wetland vulnerability to sea level rise, but are effective only in locations with abundant sediment supply. Note: they define “nature-based solutions” in the paper, which they explicitly state to include: “the creation of living shorelines through vegetation planting, hydrological reconnection of reclaimed wetlands to the sea, managed retreat from the shore through removal of flood defenses, and thin-layer sediment placement that increases wetland elevation...”
Leonardi et al. 2018	Key paper for review of relationship between storms and salt marshes, including discussion of storm impacts on marsh sediment budgets and resilience to sea level rise; great summary of impacts including diagram with citations
Doroski et al. 2019	Study of 15 unrestored and 17 restored tidal wetlands along Long Island Sound in CT, with a range of salinity, land development, and age of restoration (1 to 23 years prior to sampling). In this case restoration includes any combination of practices that restore tidal hydrology to tidally restricted wetlands (e.g., culvert replacement, tidal gate removal, installation of self-regulating gates). The authors don’t estimate TN or other pollutant removal rates, but they do provide denitrification rates, which increased significantly with time from restoration, i.e., a >5-fold increase across the sites from 1 to 20+ years. Carbon mineralization rates did not correlate strongly to time. The authors note differences in C and N process rates between freshwater and brackish sites: freshwater sites the C and N rates strongly relate to metal

	content while for brackish sites they relate to organic matter and salinity gradients. Useful discussion by the authors of denitrification citing other studies, noting that decreased denitrification potential may be driven by multiple mechanisms related to salinity (Zhou et al. 2017) such as direct microbial or enzymatic effects, formation of toxic compounds like sulfide, and mobilization of nutrients (e.g., export of soil ammonium seen in (Ardon et al. 2013))
Huang et al. 2017	Study of saltwater intrusion and restoration of freshwater hydrology to wetlands in Yellow River Estuary. Includes results of soil org-carbon, anammox and denitrification rates, as well as details of microbial communities. Key points include: (1) their incubation study suggests that denitrification is highly sensitive to salinization even in the very short term (denitrification rate dropped by 80%); (2) denitrification was the major pathway for nitrate reduction with a much higher nitrate turnover rate (15-20 times) observed after freshwater restoration; (3) while the restoration of freshwater did significantly alleviate saltwater stress and change the microbial communities, it was not efficient in recovery of storage of soil carbon and total nitrogen, which would take longer to recover if at all.
Ardon et al. 2013	Study of a project in NC, part of Great Dismal Swamp wetland mitigation bank, which includes forested wetlands and former agriculture fields. Authors suggest that the spatial extent of increased salt cations (and thus the impact of cation displacement for NH_4) is greater than the extent and effect of biological/microbial changes from increased SO_4. Much of literature has focused on SO_4 they say, but the impact of salt ions like Cl^- reaches farther inland than SO_4. That said, microbial changes are harder to understand so the relative importance of abiotic cation exchange and biotically driven changes will be important for coastal WQ. Furthermore, they point to the role that prior land use and fertilizer application history can play. Their results also suggest that a site that continually receives low levels of salinity (<5ppt) can potentially release ammonium for long periods of time, suggesting that hydrologic reconnection should be considered carefully in case it may increase frequency or intensity of saltwater intrusion and thereby constrain N retention.
Living shoreline	
O'Donnell 2017	Review of literature on design and function of living shorelines including nonstructural (marsh restoration/creation, slope/bank grading, beach nourishment, dune creation/restoration) and hybrid approaches (incorporating fiber logs, marsh toe revetment, oyster reefs, breakwaters, wave attenuation devices) with focus on applicability to New England. Though the review does not address nutrients, it summarizes literature on the effectiveness of living shoreline approaches to counter or withstand wave

	attenuation, storm surge, sea level rise, or stabilize shorelines. Excellent overview, but limited specific information to summarize here. Some key points include: Tidal marsh restoration guards against coastal erosion in low wave-energy conditions. Marsh vegetation's ability to attenuate small and medium wave heights (< 0.5m) is well documented in field and lab studies. Even a narrow fringe marsh may be effective to attenuate wave energy. Living shorelines are likely better for coastal protection when considering gradual, long-term changes than they are against shorter-term extreme events like storms.
Landry and Golden 2018	Study of 24 sub-estuaries in the Chesapeake Bay and others in the Mid-Atlantic demonstrating the negative impacts of hardened shorelines on SAVs; shoreline condition more predictive of SAV condition than landuse. Living shorelines provide more resilience to climate impacts because adjacent SAVs recover faster after large storm events than those adjacent to hardened shorelines and can migrate where coastal retreat is allowed.
Liu et al. 2021	See above for discussion of study that also applies for living shoreline given authors' consideration of "nature-based coastal protection"
Stream restoration	
Williams et al. 2017	Field study of restored wetland-stream complex for 7 years pre- plus post-construction on MD Coastal Plain demonstrating runoff reduction ~5% and pollutant reductions of ~25-28% TN, ~16-20% TP, and ~28-33% TSS. Modeling study of 23 ha developed watershed in MD, with NLDAS-II forcing of several GCMs used CBP watershed model to predict increase of 12% for precipitation, 22% for streamflow, and 66% for sediment export. Found 2-3x current BMP implementation needed to achieve pollutant reduction goals given the additional ~15-30% loading predicted with climate change, even assuming an increase in BMP efficiency of 30%. Also includes a modeling component to assess climate change impacts on stream restoration, how they can be offset, and how restoration projects can be more resilient.
Oysters (restoration or aquaculture)	
Caffrey et al. 2016	Gives some experimental results for denitrification rates by oysters (in their experiment the denitrification represented 20% of total nitrate uptake). However we expect the forthcoming oyster restoration BMP panel report will contain far more detailed and relevant data for oyster restoration in this region.
Miller et al. 2017	Study focuses on how to improve modeling for site selection in Gulf of Mexico along Louisiana coast. They discuss needs to better account for factors beyond temp and salinity, such as predation, recruitment and

	disease/infection. Among their conclusions: low salinity for extended periods especially at higher temps can kill oysters, larger oysters more resilient; frequency, duration, and timing of low salinity events important for oysters; high salinity = increased predation, high salinity + high temp = increased infection
Ridge et al. 2017	Study of marsh and oyster reef sites in Back Sound, NC Oyster reefs can help slow marsh retreat and preserve buried carbonaceous sediments from erosion. Consideration of tidal and hydrodynamic conditions of the site may enable coupled restoration and preservation efforts of oyster reefs and marsh environments to extend ecosystem functions.

Table 7. Urban BMPs

BMP/Study	Description
General/varied BMPs	
Hager et al. 2019	Thorough review of 9 stormwater BMPs from 102 articles published 2008 and later identifying knowledge gaps: • “Lack of consensus on which parameters to measure for effective BMP and LID adoption” • “High variability in reported BMP performance” • “Many BMPs are known exporters of nutrient pollutants” • “Lack of cold weather performance-specific studies for individual BMPs” • “Lack of human pathogen-related stormwater quality studies for individual BMPs” Noted potential for nutrient export by permeable pavement, infiltration trenches, bioswales (due to fertilization), bioretention, and constructed stormwater wetlands
Koch et al. 2014	Evaluates stormwater BMP N removal performance and variability based on empirical studies (ponds, wetlands, swales) as well as data from international stormwater BMP database. Very large uncertainty because studies generally only last for hours to week. They found that some instances of the BMPs act as a source for forms of N.
Yang and Lusk 2018	Review of stormwater studies; useful overview of nutrients and sources within stormwater runoff but only a general discussion of BMPs as available options to reduce loads.
Valenca et al. 2021	Not identified in original searches Authors assess four common types of stormwater practices (bioretention, grass swales, media filters, and

	retention ponds), focusing on nitrate removal. They used data from the international BMP database to compare the BMPs nitrate removal across Koppen-Geiger climate classification, and also used the data along with a review of 29 studies to understand the link between nitrate removal and system design. They found that nitrate removal by grass swales and bioretention is more sensitive to the local climate than design specifications, whereas retention ponds are more sensitive to design than to local climate. They discuss the impact of design factors for each BMP's nitrate removal, not summarized here. They also suggest that amendments can improve nitrate removal for these practices, but that selection of the amendments should be carefully made.
Giese et al. 2019	Not identified in searches Authors compare two watersheds in Montgomery Co. MD (within Clarksburg and Germantown) in close proximity, with one developed more recently using green infrastructure and infiltration type practices, while the other one was developed pre-1990s with traditional practices (dry and wet ponds, etc.). They use SWAT to evaluate the differences in runoff under future climate conditions.
Bioretention	
Kratky et al. 2017	Review of bioretention performance, including discussion of key factors affecting BMP performance, with an emphasis on research applicable to cold climates. The focus on colder climates includes greater attention to related management concerns such as road de-icing salts.
Goh et al. 2019	Review of bioretention design (in tropics), including hydrologic factors, temperate climate
Osman et al. 2019	Review that considers design of bioretention to improve N removal. The authors note that some studies have reported nitrogen leaching from bioretention sites, especially when there are large amounts of nutrients in the filter media's organic matter or from a buildup of external organic matter. The authors point to studies that show promise when combining a saturated zone for anaerobic denitrification along with aerobic conditions in the soil media when combined with a carbon source - provided that the carbon source does not introduce an excess of nutrients that can become a source of leaching.
Qiu and Wang 2013	Short review with emphasis on phosphorus leaching and matrix materials.
Roy-Poirier et al. 2010	Good review of existing literature at the time, but less recent than other studies and reviews for our purposes.
Other	
Boger et al. 2018	Review of roadside vegetated filter strips and swales, based on pollutant concentrations and not loads.

	They found that the practices were generally efficient at removing TSS, but less efficient at removing dissolved forms of nutrients or other pollutants. They identify studies reporting negative removal for various pollutants, likely due to the build-up and subsequent purge of those pollutants and other materials.
Gavric et al. 2019	Identifies knowledge gaps for urban vegetated filter strips.
Penn et al. 2017	Review of 40 studies of P removal structures. A key reference in recent ag drainage BMP panel's review (Bryant et al. 2020) which included P-removal structures.
Tyner et al. 2011	Review of BMPs for construction site erosion and sediment control.

Table 8. Notable meta-analysis, reviews or other cross-cutting or multi-BMP articles

Study	Description	Key insights
Liu et al. 2017	Review of previous reviews of urban (8) and agricultural BMP (16) studies (including the 2009 CBP report by Simpson and Weammert). Encountered a wide range of N/P/sediment removal efficiencies, finding mixed evidence of BMP function declining over time, but hypothesized variability could obscure trends.	Most studies are short-term (<4 years with many <1 yr) with lack of reporting of import factors affecting performance; currently insufficient data to determine long-term BMP function. Attributed variability within BMP type: to"local design standards, installation quality and local conditions (soils, climate and vegetation type) differences" They attribute variability in BMP function over time to: "storm events (size, intensity, and duration), time of year (seasonal changes),watershed conditions, maintenance activities, and BMP conditions at that particular time." They also conclude that the efficiencies of BMPs change over time regardless of maintenance. Need to analyze existing data and conduct long-term monitoring of BMPs with a comprehensive record of ancillary variables to support simulation of changes in BMP efficiency over time in watershed models. They provide a list of key data needed for characterizing

		BMP efficiency, which they call for future studies to include for greater consistency.
Nummer et al. 2018	Meta-analysis of BMP nutrient removal of Measured Annual Nutrient loads from AGricultural Environments (MANAGE) database with multilevel models (MLM) and propensity score matching to account for confounding factors: Pooled 330 records from 62 fields with contour farming (22), filter strips (2), terraces (7), grassed waterways (31); two also had riparian buffers	BMPs effective for removing sediment-bound nutrients, but effect on dissolved nutrients unclear: BMPs significantly reduced total P (MLM mean 58%, propensity score mean 67%), and particulate P (76%, 83%), and particulate N (64%, 67%), but not total N or dissolved N or P. Potential for large % export of dissolved N and P in 95% confidence interval. BMPs not randomly applied, in database fields with them also had significantly higher fertilizer application. Increase in nutrient loss associated with given increase fertilizer less when BMP present. Limited data to evaluate effects of fertilizer application method and crop type on BMP performance, but greater nutrient removal associated with crops receiving higher fertilizer and generating greater runoff. Need for comprehensive reporting of site environmental and management factors to better isolate effects of BMPs.
Passeport et al. 2013	Review of "ecological engineering practices" (EEP) and their N-removal effectiveness. They define EEP to include a range of practices that are designed to the benefit of both humans and nature. They review lit for 7 types of practices: (1) advanced septic systems; (2) LID structures such as bioretention; (3) permeable reactive barriers (PRBs); (4) treatment wetlands (constructed wetlands); (5) "managed riparian buffers";	The authors note available N removal estimates as well as cost estimates for each type of practice. They also suggest that some of the practices are more appropriate when the source of N is known, and they comment on placement issues to consider for each BMP.

	(6) artificial lakes and reservoirs; (7) stream restoration	
Lintern et al. 2020	Critical review of 94 studies of BMP effectiveness at the watershed scale (ag, urban, and mixed use) to identify knowledge gaps and needed research for realizing water quality improvements as nutrient concentration or load reductions.	Water quality improvement demonstrated in 43% of field studies but predicted by 60% of modeling studies, which do not adequately capture uncertainty in BMP function, particularly potential for decreased performance or nutrient export. Absence of water quality improvement attributed by reviewed studies to “known unknowns”: ● “Optimization of the location and distribution of BMPs in specific environments” (~42%) ● “Lack of knowledge about BMP function” (~25%) ● “Lag times between BMP implementation and water quality improvement” (~18%) ● “Social, economic, and political issues” (10%) ● “Post-implementation BMP failure” (~4%) Climate change anticipated to increase nutrient loads and decrease BMP function. Long-term BMP monitoring critical to understanding BMP function generally and impacts of climate change, particularly extreme precipitation events, specifically.

Table 9. Climate impacts and their possible effects on nutrient and sediment pollution reduction mechanisms.

Climate Impact:	**CO_2: increased atmospheric concentration**	**Temperature: increased atmospheric temperature**	**Precipitation: changes in volume, intensity, and seasonality**
Pollutant Removal Mechanism			
Sediment			
Settling · A physical, hydraulic process via reducing runoff velocity · And/or increasing infiltration ·Can involve vegetation	Potential to increase plant growth, increasing settling efficiency	Can affect vegetation positively or negatively depending on season (e.g., early spring vs. summer heat wave) Potential to increase ET and reduce soil moisture	Removal efficiency reduced by increased hydraulic loading. Can increase clogging. Potential to mobilize and export sediment.
Trapping · Physical filtering and burial · Can involve vegetation · Important for colloidal/fine particles difficult to settle	Potential to increase plant growth and trapping capacity	Can affect vegetation positively or negatively depending on season (e.g., early spring vs. summer heat wave) Potential to increase ET and reduce soil moisture	Can affect vegetation positively or negatively depending on timing. Removal reduced by increased hydraulic loading. Can increase clogging. Potential to mobilize and export sediment.
Erosion protection or prevention · Stabilization or erosion prevention via plants or hard structures	Potential to increase growth of vegetation providing stabilization	Can affect vegetation positively or negatively depending on season (e.g., early spring vs. summer heat wave). Potential to increase ET and reduce soil moisture	Increased precipitation intensity and volume can reduce efficiency

Direct collection or removal	NA	NA	Increased precipitation intensity and volume can reduce efficiency
Nutrients			
Biological · Assimilation · Transformation · Uptake	Potential to increase growth of vegetation and uptake; alterations of stoichiometric ratios changes nutrient cycling	Increased temperatures increase biological rates and transformations. Potential to increase ET and reduce soil moisture changes nutrient cycling	Increased precipitation volume and variability alters rates
Physiochemical · Sorption · Precipitation · Fixation	NA	Increased temperatures increase physicochemical cycling rates and transformation products. Potential to increase ET and reduce soil moisture alters physicochemical processes	Increased precipitation volume can result in alterations to pH, increased soil moisture
Input reduction or control · Management of rate/amount of fertilizer, manure, feed or other inputs to reduce nutrients that enter the system	Potential to increase growth of vegetation and uptake requiring additional nutrient applications	Increased nutrient cycling rates can increased the need for additional nutrient applications	Precipitation variability and timing can impact nutrient retention
Direct collection or removal	NA	NA	Increased precipitation intensity and volume makes timing of collection and removal critical

Question 2b How does climate change affect BMP performance variability?

To identify studies evaluating the effects of climate change on BMP performance we queries all databases in the Web of science by topic with the following terms: “(("climate change" OR "climate uncertainty" OR "climate extremes" OR "climate variability") AND ("best management practice" OR "conservation practice" OR "stormwater management") AND ("nitr*" OR"phosphorus" OR "sediment" OR "water quality" OR "nonpoint source pollution" OR "diffuse pollution"))”. Results were updated weekly with an automated search for new publications. The only criterion for inclusion was that the study predicted how BMP removal of nitrogen, phosphorus, or sediment would be expected to change under future climate. The search yielded 75 results, 11 of which were determined to meet inclusion criteria and 63 of which were excluded. All of the studies obtained with this search simulated climate impacts using hydrologic models. We were unable to find any studies employing the conceptual approach we apply above in the peer-reviewed literature, although undoubtedly others have undertaken similar research, perhaps better represented in the “gray” literature. Table 10 summarizes the findings of eight of these modeling studies (four are discussed below but are not included in the table because their findings are not well captured in that format (Chichakly et al. 2013; Wallace et al. 2017; Woznicki and Nejadhashemi 2014; Xu et al. 2019). Three additional articles cited by those identified in the systematic search are also summarized in Table 10; it is unclear why they did not appear in initial search results. All of these studies used a variation of SWAT. Three of the watershed simulation studies evaluate the role of BMPs under climate change specifically within the Chesapeake Bay watershed (Renkenberger et al. 2016; Wagena and Easton 2018; Xu et al. 2019). However, all of the studies provide relevant insights and are discussed.

Table 10. Summary of watershed simulation studies evaluating the effect of climate change on nitrogen, phosphorus, and sediment removal with best management practices.

Source and Watershed Characteristics	**Climate Predictions**	**Watershed Responses**	**BMPs**	**BMP Responses at Watershed Scale**	**Climate models/ scenario/ time span/ watershed model**
(Bosch et al. 2014a) 4 Lake Eerie sub-basins in MN/IN/OH 1896 to 17,030 km^2 majority agriculture (3) or forest (1) 27-80% row crop , 3-19%, 9-11% urban 8-52% forest	A1F1 precip +6% snow -35% B1 precip +3% snow -14%	A1F1 streamflow +12% sediment +23% TP +6% SRP +3% NO_3^- +18% TN +16% B1 flow +6 sediment +9% TP +4% SRP -2% NO_3^- +8% TN +6%	- no-till, - cover crops, - filter strips BMP baseline = current levels	Calculated from tables and averaged over 4 watersheds: % change in efficiency (% removal)/% change in mass removal A1F1 sediment -6%/+12% TP -<1%/+31% SRP -16%/+5% TN -3%/+12% NO_3^- +<1%/+13% B1 sediment +7%/+12% TP +9%/+26% SRP -18%/-5% TN +4%/+11% NO_3^- +7%/+13%	GFLD21, HadCM3, PCM B1, A1F1 2010-2099 SWAT
Chiang et al. 2012 AK, 32 km^2 Lincoln Lake Watershed, CEAP	2010-2069: Precip -10% to +6% Min temp +1.1C to +3.1C	Change in loads assuming current BMP levels (34% watershed) Historical climate/future	Pasture BMPS: - nutrient management - filter strips, - grazing management	Optimal BMP combination future without climate change % reduction: TSS 17.6% TN 28.6% TP 74.7%	CCSM, CGCM2, GFLD21 Historical: 1992-2007 Future:

48.7% forest, 35.8% pasture, 11.8% urban, 1.5% urban-commercial, 2.2% other rapid urbanization (pasture reduced 47.6% to 35.8% in 8 years)	Max temp +1.2C to +3.4C	without climate change: TSS 0.16/0.16 t ha^{-1} TN 4.00/3.85 kg ha^{-1} TP 1.05/1.19 kg ha^{-1} Future climate range for 3 GCMs: TSS 1.08-1.78 t ha^{-1} TN 3.56-4.57 kg ha^{-1} TP 1.00-1.29 kg ha^{-1}		future with climate change % reduction (GCM range): TSS 1.3-4.4% TN 22.2-25.5% TP 70.1-72.6%	2010-2069 SWAT 2009
Jayakody et al. 2014 MS, 7588 km^2 72% forest, 20% pasture, 6% residential, 2% crop	<u>2046-2065:</u> Temp A1B +2.1C A2 +2.2C B1 +1.6C Precip (all) +6.3% to +11.8% <u>2080-2099:</u> Temp A1B +2.8C A2 +2.4C B1 +1.6C Precip (all) +8.3% to +13.1% <u>1992-2011 baseline:</u> temp 24C	<u>2046-2065:</u> flow +4.2 to +16.2% Sediment +8.4% to +22.2% TN -0.5% to +7.3% TP -3.9% to +9.2% <u>2080-2099:</u> flow +19.0% to +19.5% Sediment +24.9% to +26.3% TN +2.1% to +5.5% TP +11.3% to 14.3% <u>1992-2011 baseline:</u> Streamflow 90 m^3s^{-1} Sediment 0.49 mg ha^{-1} yr^{-1}	- stream fencing - riparian forest - buffer - filter strip - nutrient management	Watershed-scale, practices combined load removal <u>1992-2011 baseline:</u> Flow 51% Sediment 55.5% TN 44.4% TP 88.6% <u>2046-2065:</u> Flow 40.6% Sediment 46.2% TN 50.8% TP 89.5% <u>2080-2099:</u> Flow 38.5% Sediment 43.5% TN 45.3%	CCSM3 SWAT A1B, A2 and B1 Mid-century (2046-2065) late-century (2080-2099)

	precip 1340-1527 mm (across 10 weather stations)	TN 6.3 mg ha^{-1} yr^{-1} TP 10.7 mg ha^{-1} yr^{-1}		TP 87.7%	
Park et al. 2014 South Korea, 6642 km^2 82.3% forest, 12.2% agriculture (~90% paddy, 10% upland crops), 2.6% grassland, 2.9% other 37% average slope	2031-2060: A1B Precip +16.4% Temp +1.6C B1 Precip +6.0% Temp +1.4C 2071-2100: A1B Precip +19.5% Temp +3.7 B1 Precip +19.4% Temp +2.6C (1981-2010 baseline)	Changes in flow and loads of sediment, TN, and TP only presented graphically; appears all may decrease in future climates.	- streambank stabilization - porous gully plugs - recharge structures - terraces - contour farming	Streambank stabilization: greatest and most consistent removal in all scenarios to baseline for sediment (94.3-97.2%) and TN (69.1-75.4%) Porous gully plugs captured more sediment but released more nutrients in future climate. Recharge structures ineffective for nutrient removal in current climate, but significant TP removal in future climate.	MIROC3.2 A1B, B1 Mid-century: 2031-2060 Late-century: 2071-2100, SWAT
Qiu et al. 2020 Miyun Reservoir Watershed, China, 14,924 km^2 warm temperate	Reported graphically Increased temperature increased ET and reduced soil moisture and runoff, especially in summer and for RCP8.5	Reported graphically Increases in sediment, N, and P loads over baseline corresponded to increases in precipitation intensity and volume during flood season	- conservation tillage - residue management - contour farming - alley cropping - conversion of farmland to forestland - fertilizer reduction, - filter strips - constructed wetlands -grassed waterways - detention basins	Average change in reduction efficiency for all BMPs: <u>All RCP:</u> Runoff -0.8% to -0.6% Sediment -1.2% to -1.9% TN -1.1% to -1.3% TP -1.9% to -2.1%	GFDL-ESM2M, HadGEM2-ES, IPSLCM5A- LR, MIROC-ESM-CHE M, NorESM1-M RCPs 2.6, 4.5, 8.5 Historical: 1980-2004

continental monsoon 49% forest, 22% agriculture, 27% rangeland, 2% other	Increased high intensity precipitation during flood season	For each 1C increase for RCP8.5, TN loads increased 3.77% and TP loads increased 4.51%			Future: 2020-2099 SWAT
Renkenberger et al. 2017 Choptank sub-basin MD, DE 298km2 49% agriculture, 34% natural, 6% urban (Climate modeling from (Renkenberger et al. 2016); see also Tables 3 and 4)	2081-2100 B1 precip +25% flow +57% A1B precip +30% flow +82% A2 precip +29% flow +90%	2081-2100 B1 TSS +70% TN +56% TP +52% A1B TSS +117% TN +88% TP +64% B2 TSS +132% TN +69% TP +78%	evaluated “generic BMP” to determine what BMP efficiency would be needed to mitigate increased pollutant loads of future climate, not how performance of a specific BMP would be altered	Needed reductions for TMDL (% watershed targeted): baseline TSS 33% TN 45% TP 23% 2081-2100 B1 TSS 63% TN 64% TP 49% A1B TSS 69% TN 70% TP 53% A2 TSS 71% TN 67% TP 57%	GFDL CM2.1 AOGCM B1,A1B, A2 mid-century 2046-2064 end-century 2081-2100 SWAT

Schmidt et al. 2019 GA Coastal Plain, 1624 km^2, cropland (% not specified) MN, 338 km^2, 86% cropland	historic to late-century, range for 5 GCMs GA: precip -9.1% to +10% temp +3.8C to +5.6C crop biomass -10% to 25% by late-century MN: temp +5.9C by late century	Without BMPs, GCM average GA: 2030-2059 sediment +33% TP +45% NOx no difference TN no difference 2070-2099 sediment +75% TP +165% NOx -2.7% TN -2.2% MN: 2030-2059 sediment +8% TP +19% NOx +46% TN +43% 2070-2099 sediment +38% TP +54% NOx +85% TN +82%	- conservation tillage - no-till (GA only) - grassed waterways (GA only) - filter strips - nutrient management - drainage water management (MN only)	Average change in % removal (range over 5 GCMs) GA: sediment -4.8% (-3.2% to -6.1%) TN -13% (-8.4 to -17) TP -2.5% (-5.3% to +0.3%) MN: sediment -3.1% (-1.4% to -5.0%) TN -0.7% (-0.2% to -2.0%) TP -0.70% (-1.5% to +0.3%)	CMIP5 RCP8.5 Baseline (1951-2005) mid-century (2030-2059) late century (2070-2099) SWAT
Van Liew et al. 2012	B1 Tmax +1.8C Tmin +1.7C snowfall SC -22%, LC -6%	Shell Creek: B1 flow +20% sediment +23%	- crop conversion to switchgrass - crop conversion to pasture - terraces	Not provided numerically; authors state BMP efficiency in current and future climate similar at the	CMIP3 B1, A1B, A2

NE, 1214 km2 74% row crops, 19% range, 3% alfalfa, 2% other Shell Creek: 1990 km2 84% row crops, 14% range, 2% alfalfa Logan Creek: output variables evaluated at reaches drawing 781 and 785 km2 to aid comparison	precip SC +3.1%, LC 6.4% A1B1 Tmax +2.3C Tmin +2.4C snowfall SC -22%, LC -22% precip SC +2.3%, LC 6.9% A2 Tmax +2.0C Tmin +2.2C snowfall SC -27%, LC -22% precip SC +2.2%, LC 5.8%	TN +22% TP -3% A1B flow +29% sediment +43% TN +26% TP +14% A2 flow +41% sediment +49% TN +42% TP +6% Logan Creek: B1 flow +45% sediment +98% TN +75% TP +50% A1B flow +52% sediment +146% TN +88% TP +74% A2 flow 52% sediment +92% TN +87% TP +74%	- buffer strip - no-till	watershed-scale but varied at the field-scale	baseline 1980-2000

Wagena and Easton 2018 Susquehanna River Basin 71,200 km2 (42% of Chesapeake Bay watershed) 70% forest, 22% agriculture, 7% developed, 1% water (See also Tables 3 and 4)	mean precip mid-century +3.8% late-century +6.5% temp 2041-2065 min +2.8C max +1.9C 2075-2099 min +2.7C max +1.7C ET 2041-2065 +4.7% 2075-2099 +7.4%	flow +4.5+/-7.3% runoff +3.5+/- 6.1% sediment +28.5+/-18.2% TN +9.5+/-5.1% NO3- -12+/-12.8% TP -2.5+/-7.4% DP -14+/-11.5%	-buffer strips -strip-cropping -no-till -tile drainage	watershed-scale reductions BMPs vs. no practices: mid- and late-century: sediment BMPs combined: 20.4-20.8% NO3: buffers 9.3-11.5% no-till 2.1-3.8% strip crop 2.3-4.1% tile drainage *increased* export 14.8-15.2% TN: buffer 11.4-17.1% tile drainage 6.1%-10.2% no-till 1.3-2.3% strip crops 2.9-5.8% TP tile drainage 12.6-14.5% buffer 14.2-16.4% no-till 3.4-5.1% strip crop little effect DP tile drainage 37.4-39.0% buffers 29.4-36.9% no-till 7.8-13.4% strip crop 4.3-11.1%	CMIP5, 6 GCMs and ensemble mean RCP2.6,, RCP8.5 historic (1990-2014) mid-century (2041-2065) late-century (2075-2099) SWAT-VSA
Woznicki et al. 2011 KS/NE 6158 km2	A1B precip +14.6% ET +11.3% ET runoff +42.9% baseflow +61.5%	A1B sediment +54% N +37% P +30% A2	-no-till - conservation till - contour farming - terraces - filter strips - porous gully plugs	Tables 12-13 provide change in BMP efficiencies at the HRU and watershed scale Discussion suggests median removal efficiencies similar across climate scenarios, but	CCSM-3 B1, A1B, A2 SWAT

40% row crops, 42% rangeland, 9% forested, 4% urban, 5% other	<u>A2</u> Precip +11.1% ET +8.9% runoff +29.8% baseflow +46.1% <u>B1</u> precip +8.5% ET +7.2% ET, runoff +18.3% baseflow +26.9%	sediment +36% N +27% P+22% B1 sediment +20% N +11% P +12%	- grazing management - native grass/alternate crops	variability increases for contour farming, native grass, and terraces	

Modeling BMPs in Future Climates

Bosch et al. (2014a): The effect of climate change on agricultural BMPs (no-till, cover crops, and filter strips) for A1 and B1 climate scenarios was evaluated in four sub-basins within the Lake Erie watershed. Climate factor changes over the mid- to late-century included warming (disproportionately in the winter months), reduced snowfall, and increased precipitation volume and intensity (particularly in the winter and spring). Sediment yields exhibited the largest and most consistent response across the four sub-basins, averaging +23% by 2100, and the intensity of spring rainfall events during tillage was highlighted as a driver. Nutrient loads also increased under future climates, but this response was more variable across the four watersheds. BMP pollutant removal efficiency tended to increase slightly under the B1 scenario (+4% to +7% depending on the constituent, except soluble phosphorus, which decreased by 18%) and decrease under the more extreme A1F1 scenario, though relatively little for TP (<-1%) and TN (-3%). One mechanism for decreased BMP effectiveness was the increased infiltration during warmer winters (without frozen soil or snow cover) transferring more of the nutrient load from the surface to subsurface, by passing the filtering and plant uptake nutrient removal mechanism of the BMPs. (Bosch et al. 2014a) note that cover crops and no-till are most effective for reducing the loss of sediment and nutrients in winter and early spring, so this seasonal effect was particularly significant. Although this scenario may have limited relevance for the Chesapeake Bay watershed, it emphasizes the importance of nutrient transport pathways. More broadly, the ability of large storm events to overwhelm nutrient and sediment removal processes in BMPs was also cited. However, the decrease in efficiency masked increases in pollutant mass removal; load reductions increased 11% to 13% for TN, 26% to 31% for TN, and 12% for sediment. Nonetheless, (Bosch et al. 2014a) concluded that climate-induced increases in pollutant loads exceeded reductions achievable BMP implementation at an intensity considered acceptable to stakeholders (to ~30% of agricultural land) and near full implementation of BMPs on all agricultural land was required to offset increased loads. Another notable conclusion from this study was the suggestion that “threshold climate change” may dramatically increase pollutant export, evidenced by the larger pollutant yields under the more pronounced climate scenario.

Chiang et al. (2012): The performance of pasture management BMPs (nutrient management, vegetated filter strips, and various grazing management strategies) was evaluated, and optimal combinations were identified through mid-century with and without climate change applied in a 32 km2 watershed in Arkansas. With the climate models predicting a range of precipitation changes (-10% to +6%, generally a decrease in the short-term followed by an increase toward mid-century) and temperature increases approximately 1-3C for both annual minima and maxima, with existing levels of BMPs in place TN and TP export remained constant but sediment export increased an order of magnitude and was correlated with precipitation. Consequently, under future climate BMP sediment removal efficiency dramatically decreased from 17.6% to 1.3-4.4%. Under the optimal BMP scenario, TN reductions achieved under future climate (22.2-28.6%) were not as high as under the current climate (34.6%), while TP reductions slightly increased in future climates (from 68.6% to 70.1-74.7%). Interestingly, (Chiang et al. 2012) concluded that nutrient reductions with pasture BMPs were more stable in future rather than historical climate.

Jayakody et al. (2014): Stream fencing, riparian forest buffers, vegetated filter strips, and nutrient management were assessed in a 7588 km2 watershed in Mississippi under climate scenarios B1, A1B, and B2 for mid- and late-century. By 2080-2099, temperature increases were 1.6-2.8C, precipitation increases were 8.3-13.1%, and streamflow increased 19.0-19.5%, depending on the climate scenario. Pollutant loads also increased, 24.9% to 26.3% for sediment, 2.1 to 5.5% for TN, and 11.3 to 14.3% for TP. Pollutant load removal for BMPs combined at the watershed scale decreased significantly for sediment (from 55.5% to 38.5%) but remained relatively constant under future climate for TN (44.4% vs. 45.3%) and TP (88.6% vs. 87.7%)--though these impacts mainly reflect the performance of vegetative filter strips given the composition of the watershed. The reduction in BMP sediment removal efficiency was attributed to the effect of increased precipitation intensity on filter strip performance.

Park et al. (2014): Although focused on a South Korean watershed with very different climate (humid continental) and cropping systems (90% rice paddy) than the Chesapeake Bay, this study provides a useful perspective on the differing responses to future climate across BMPs and the potential tradeoffs of these responses with respect to particular pollutants. In a 6642 km2 watershed dominated by forest (82.3%) but with significant agricultural land use (12.2%), Park et al. (2014) examined under the AIB and B1 climate scenarios the performance of streambank stabilization (larger streams>3rd order), gully plugs (in ephemeral channels), recharge structures (small dams in tributary streams to promote infiltration), terrace and contour farming. Streambank stabilization had the highest sediment (97.2%) and N (75.4%) removal efficiency, and performance was predicted to only slightly decline under future climate (to about 94% and 70%, respectively). Slope terracing had the highest TP removal efficiency (69.8%), which was largely maintained under future climate (~60-80% removal) along with high sediment reduction (86% for the B1 scenario and 70% for the A1B scenario). However, TN export with slope terracing increased from 5% to 20-23% with climate change. Porous gully plugs also exhibited a tradeoff between nutrient and sediment removal; while they had little effect on pollutants under historical climate conditions (having no effect on sediment and removing 4-6% of TN and TP), under future climate conditions they could remove ~50% of the sediment load but increased TN loads by 20% and TP loads by 35%. In contrast, recharge structures, which had little effect on nutrients in the current climate, were able to remove significant TP under future climate conditions (~10-50% depending on the climate scenario and time period), though they also exported TN (~16-22%). Though changes in annual sediment and nutrient loads were not reported numerically and appeared not to change significantly, there were notable changes in the seasonality; a notable increase in streamflow along with sediment, TN, and TP loads in March was attributed to earlier snowmelt with warming temperatures. Seasonal differences in hydrologic and watershed conditions affected BMP performance even when annual loads were not significantly changed, the authors noted the importance of developing BMP strategies that account for these temporal changes in pollutant loads.

Qiu et al. (2020): The response of a range of agricultural BMPs was evaluated in the 14,924 km2 Miyun Reservoir watershed in China (characterized by 49% forest, 22% agriculture, 27%

rangeland, 2% other landuse) where the effects of climate change are already decreasing streamflow, increasing erosion rates, and resulting in more frequent droughts. Simulation of RCPs 2.6, 4.5, and 8.5 through the end of the century resulted in further increases in temperature, winter precipitation, and extreme precipitation while decreasing summer precipitation. RCP4.5 produced the largest increases in precipitation volume and intensity. In this warm temperate continental monsoon climate, nutrient and sediment loads were significantly increased during flood season for all climate scenarios. Qiu et al. (2020) report that increases in precipitation volume and intensity were the main drivers of increased pollutant export, with high correlation between monthly precipitation and sediment, N, and P loads. They also found that nutrient loads were correlated with temperature; for each 1C increase, TN loads increased 3.77% and TP loads increased 4.51% under climate scenario RCP8.5. Redundancy analysis was used to evaluate the relationships between BMP efficiency for a given pollutant with the climate factors precipitation, temperature, solar radiation, relative humidity, and wind speed. This analysis demonstrated some intuitive relationships (such as an inverse correlation between precipitation and removal efficiency for all pollutants and nearly all BMPs) and some differences in response with respect to different pollutants (solar radiation was positively correlated with TP removal but not the other constituents); the spread between BMP types was not very large, however, suggesting that they responded relatively similarly to the climate factors. However, the discussion and interpretation of this RDA analysis by (Qiu et al. 2020) seemed limited to applying apriori understanding to explain their results. Though the analytical approach was interesting in its incorporation of BMP response to climate factors not typically evaluated directly in these climate change simulation studies, the utility of its application here was limited.

They concluded that BMPs remained effective under future climate conditions, with efficiencies predicted to decrease only slightly, on the order of 1 to 2% at the watershed scale averaged over all the practices evaluated; there were much larger differences in pollutant removal between BMP types than within BMP type across different climate scenarios. However, it is notable that the performance of what they termed “structural BMPs”--including filter strips, constructed wetlands, and grassed waterways, which function by intercepting, slowing, and treating surface runoff and are dependent on adequate residence time for treatment – was reduced more under future climate than non-structural BMPs, including conservation tillage and residue management. Notably, filter strips, constructed wetlands, grassed waterways, and detention basins had some of the highest median pollutant removal efficiencies, but also the largest performance variability across the watershed subbasins. Even with relatively small changes in BMP performance, the increase in pollutant loads predicted under future climate required more widespread BMP application to achieve the same water quality goals. Qiu et al. (2020) conducted a redundancy analysis (RDA), displayed as Figure 22 here, to evaluate the relationships between BMP efficiency for a given pollutant with the climate factors precipitation, temperature, solar radiation, relative humidity, and wind speed. The analysis demonstrated some intuitive relationships (such as an inverse correlation between precipitation and removal efficiency for all pollutants and nearly all BMPs) and some differences between pollutants (solar radiation was positively correlated with TP removal but not the other constituents). However, the discussion and interpretation of this RDA analysis by Qiu et al. (2020) seemed limited to applying apriori understanding to explain the results, though the analytical approach was interesting in its incorporation of BMP response to climate factors not typically evaluated directly in these climate change simulation studies.

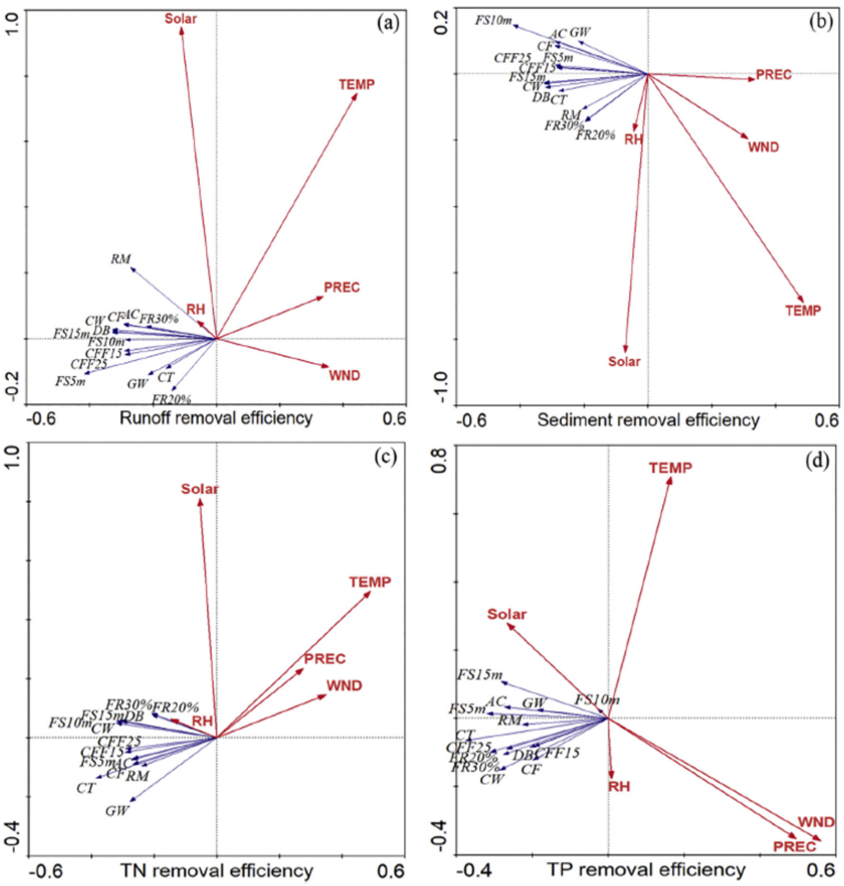


Figure 22. Relationships between annual runoff (a), sediment (b), TN (c), and TP (d) removal efficiencies of 14 BMPs with climate factors, including precipitation (PREC), temperature (TEMP), solar radiation (Solar), relative humidity (RH), and wind speed (WND) during 2020-2099. From Qiu et al. (2020), Figure 5.

Renkenberger et al. (2017): This study was conducted in the Greensboro Choptank sub-basin of the Chesapeake Bay watershed, and thus is of high relevance to this review. Renkenberger et al. (2017) took a unique approach to evaluating climate impacts on BMPs among the studies summarized in Table 10. Rather than evaluate the change in BMP efficiency as a result of the change in pollutant loading and direct climate impacts to practices modeled dynamically in SWAT, they determined the efficiency required of a "generic" BMP applied to a targeted proportion of the watershed to achieve TMDL water quality goals under future climate conditions. Applying the critical source area concept, the 20% of hydrologic response units (combination of land use and management defining, among other qualities, ability to generate pollution in SWAT) responsible for the most nitrogen, phosphorus, and sediment under current and future climate under the A1B and A2 climate scenarios. Due to predicted increases in precipitation volume and intensity, the watershed area accounting for pollutant export rates above the threshold defined by the top 20% of HRUs increased for the A2 scenario relative to historical conditions from 18% to 45% for TSS, 11% to 29% for TN, and 13% to 32% for TP. Combining the top source areas for each pollutant, under current climate conditions, 31% of the watershed would need to be treated with BMPs achieving removal efficiencies of 61% for TSS, 79% for TN and 43% for TP. Strikingly, under the A2 climate scenario, the watershed area requiring treatment would increase to 58% and required pollutant reduction efficiencies would increase to 82% for TSS, 74% for TN, and 72% for TP to meet the TMDL. Given that land use in the 298 km2 Choptank sub-basin is 49% agriculture, 34% natural, and 6% urban, some of the pollutant export from natural land would require mitigation. Renkenberger et al. 2017 starkly state that “A false sense of security may result from implementing BMPs on all agricultural and urban lands in the watershed (an over-design relative to a CSA targeting approach), and stakeholder frustrations may emerge as water quality remains unimproved, or worsens, with the changing climate.” Indeed, they found that applying BMPs to all agricultural and urban land would not achieve TN reduction targets under future climate even with 100% removal, and the 75-95% BMP efficiencies required for other constituents (except soluble P, where only 55-60% removal would be required). BMP application of achieving TMDL goal under current climate conditions would result in TMDL exceedence greater than 100% for TSS and TN and on the order of 60% to 80% for TP.

Schmidt et al. (2019): The change in BMP efficiency was evaluated in two agricultural watersheds, a 1634km2 watershed in the Georgia Coastal Plain and in a 338km2 watershed in Minnesota; given its greater relevance to the Chesapeake Bay, results from the Georgia watershed are discussed. Over the range of CMIP5 GCMs for the RCP8.5 scenario, while temperature consistently increased from +3.8C to 5.6C, changes in precipitation varied significantly from -9.1% to +10. Schmidt et al. (2019) were the only study from Table 10 also reporting the change in crop biomass (largely cotton and peanuts in the study area), which ranged from -10% to +25%. By the end of the century, generated pollutant loads increased by 75% for sediment and 165% for TP, but actually declined somewhat for TN, -2.2%. Additionally, variability and uncertainty in pollutant export increased toward the end of the century.

The effects of temperature and soil moisture changes on biologically mediated processes affected BMP performance differently in various climate change scenarios. The combined effects of temperature and precipitation changes were important for practices dependent on plant growth, including vegetated filter strips and grassed waterways. Efficiencies of these practices increased slightly for climate realizations with relatively lower precipitation and higher temperatures, reducing the flow and providing more opportunity for sedimentation and infiltration. In contrast, practices for managing crop residue, conservation tillage and no-till, were sensitive to temperature–high temperature enabling more rapid degradation of crop residue and reducing performance–but insensitive to whether precipitation increased or decreased. Perhaps the BMP most significantly affected by future climate conditions was cover crops, since they were the most efficient practice for reducing sediment, maintaining greater than 70% reduction in current and future climates. Warmer winter temperatures improved winter cover crop growth and sediment removal but also increased mineralization rates of cover crop residue and thus N and P export. Overall, average BMP efficiency was decreased under future climate for all constituents, -4.8% for sediment, -13% for TN, and -2.5% for TP, trending downward to the end of the century. Schmidt et al. (2019) cite the causes of decreased efficiency not only as increased loading (though TN loading was not predicted to increase due to increases in ET and reduced subsurface transport), but also increases in precipitation intensity yielding increased runoff and changes to biologically-mediated processes under higher temperatures and altered soil moisture. One notable conclusion was that BMP performance in the southeast may be more negatively impacted than in the midwest. However, the evidence for this statement is limited, given that Schmidt et al. (2019) offer support for this conclusion in more moderate temperature increases but more reduced BMP performance in the GA watershed compared to the MN watershed (findings not discussed here) though suggest changes in performance are more driven by precipitation; enhanced cover crop performance in warmer winters in the midwest under future climate may also support this conclusion. In terms of overall climate impacts on water quality, in contrast to Renkenberger et al. (2017), Schmidt et al. (2019) concluded that increased agricultural BMP implementation could offset increased pollutant loading under future climate conditions.

Van Liew et al. (2012): Two similar watersheds in Nebraska (approximately 1200 km2 and 2000 km2, both dominated by row crops and rangeland) were evaluated under future climate conditions to the end of the century for the B1, A1B, and A2 scenarios. Moderate increases in minimum and maximum annual temperatures from +1.7C to +2.4C and in precipitation from +2.2% to +6.9% resulted in significant increases in streamflow (+20% to +52%) pollutant loads (up to +146% for sediment, +88% for TN, and +74% for TP under the A2 scenario), but little impact on the BMP efficiency. These findings in Midwestern agricultural watersheds differ from Bosch et al. (2014a), who found reduced BMP effectiveness. Though studies from the Great Plains region may have limited transferability to the Chesapeake Bay watershed, as pointed out by Renkenberger et al. (2017), a cautionary conclusion of Van Liew et al. (2012) worth noting is the sensitivity of flow and pollutant loads to both calibration (the soil evaporation compensation factor in particular), suggesting considerable model uncertainty in the results.

Wagena and Easton (2018): With the Susquehanna River Basin as the study area (71,000 km2 and 42% of the Chesapeake Bay watershed), this watershed simulation study most directly addresses the effect of BMPs on the Chesapeake Bay under future climate conditions, though they do not compare future BMP performance to a historical baseline. Wagena and Easton (2018) used SWAT-VSA to model the impact of buffer strips, strip-cropping, no-till, and tile drainage on water quality with an ensemble of six CMIP5 GCMs. The ensemble mean increase in precipitation was +3.8% and +6.5% for mid-century and late-century, respectively. Annual minimum temperature increases (+2.7C and +2.8C) were greater than annual maximum temperature increases (+1.9C and +1.7C). Along with increased temperature, ET was predicted to increase substantially by +4.7% mid-century and +7.4% late-century. While streamflow and runoff were predicted to increase (+4.5+/-7.3% and +3.5+/- 6.1%, respectively), the variability in these predictions encompassed slight decreases, reflecting greater uncertainty in these hydrologic variables. Unlike some of the previously described studies, nonpoint source pollutant loads exhibited a mixed response to future climate; while sediment loads increased (+28.5+/-18.2%) as did TN loads (+9.5+/-5.1%), inorganic nutrients decreased (nitrate -12+/-12.8% and dissolved P -14+/-11.5%). Dissolved P load reductions yielded TP load reductions, though the variability suggested the possibility of a slight load increase (-2.5+/-7.4%). Despite the range in predicted precipitation driving variability in nonpoint source pollution generation, sediment losses increased, even for climate models that predicted reduced runoff, due to increased precipitation intensity and a shift in precipitation timing, a greater proportion occurring in the winter when the soil is less protected by vegetation. The reduction in dissolved P loads was caused by decrease in mineralization of soil organic matter (11.8% mid-century and 18.2% late-century), while the reduction in nitrate loads due to increases in denitrification with warmer temperatures. They evaluated the ability of agricultural BMPs to mitigate the effects of climate change on water quality and demonstrated that the existing levels of implementation are insufficient to meet the TMDL. As a strategy for increased BMP implementation, targeting agricultural critical source areas, here the 30% of agricultural land producing the most pollution, resulted in nearly the same pollution reductions as widespread implementation across the watershed was able to achieve.

<u>Woznicki et al. (2011):</u> This study evaluated agricultural BMPs in a ~6200 km watershed spanning Kansas and Nebraska dominated by row crops (40%) and rangeland (42%). Though the authors found median BMP efficiency in current and future climate were similar at the watershed scale, despite large increases in runoff and baseflow (up to +42.9% and +61.5% in A1B) along with nonpoint source pollutant loads (+54% for sediment, +37% for N, and +30% for P). However, removal efficiencies of the eight BMPs evaluated tended to vary at the field-scale across the climate scenarios (B1, A1B, and A2), except for porous gully plugs and filter strips, whose effects were unchanged. Sediment removal efficiency increased at HRU-scale except for grazing management, native grass, and porous gully plugs, though this increased field-scale efficiency was masked at the watershed-scale. TN and TP removal efficiency decreased in at least one climate scenario at the watershed-scale for all BMPs except conservation tillage. Gully plugs, conservation tillage, and filter strips had lowest efficiencies but also lowest variability.

<u>Woznicki and Nejadhashemi (2014):</u> Assessed BMP performance uncertainty under climate change with Latin Hypercube Sampling for range of agricultural BMPs in the same KS/NE watershed studied by Woznicki et al. (2011). Cumulative distribution functions were developed for each BMP under each climate scenario for removal efficiency of each pollutant (Fig. A1), demonstrating that performance uncertainty increases under climate change. Unsurprisingly, with increasingly extreme climate change scenarios, BMP uncertainty further increases. Like Park et al. (2014), Woznicki and Nejadhashemi (2014) also found the relative effectiveness of BMPs can change under different climate scenarios. In addition, BMP uncertainty was found to vary both temporally (Fig. A2) and spatially (Fig. A3), and these patterns were in turn affected by the climate scenario. Of the BMPs evaluated, grazing management exhibited some of the highest pollutant removal efficiencies, but also the greatest uncertainty, demonstrating both the increased complexity in responses to climate change in BMPs integrating more biological processes to achieve pollution reduction and the tradeoff between the relative performance and relative risk of practices.

Though the modeled distribution of pollutant load reductions achieved by BMPs (Fig. A2) under current and future climate appear to be symmetrical–or at least their symmetry is unchanged by climate impacts–probability density functions with long left tails, derived from quantitative field data developed by others in large meta-analyses Koch et al. (2014) for stormwater practices and Liu et al. (2017) for a combination of agricultural and stormwater practices), suggest a greater risk of underperformance, and even the possibility of pollutant export in some cases (see Figs. A4 and A5). Other studies assessed in question 2a, including the stormwater BMP review by Hager et al. (2019), an agricultural BMP review by Nummer et al. (2018), and a mixed review of ag and urban BMPs by Lintern et al. (2020), also noted the potential for BMP nutrient export.

Other studies: Several other studies addressed the ability of BMPs to achieve water quality goals under future climates without directly evaluating their change in performance.

- Chichakly et al. (2013): A conceptual framework for evaluating the robustness of stormwater management practices to future climate conditions by testing sensitivity to precipitation patterns, using multiobjective optimization to select cost-effective BMP application scenarios maximizing sediment reductions but not compromised by increased precipitation intensity. They recommended optimization under the strongest climate forcing to produce solutions robust to a range of climate change scenarios.
- Wallace et al. (2017) (from Q2a): Sediment and nutrient reductions for implementation of several agricultural BMPs applied in isolation or combination across a 42 km2 row crop-dominated watershed in Indiana were modeled in SWAT for future climate utilizing an ensemble of 16 CMIP5 GCMs. Watershed reductions in pollutant loads were reported as compared to current management levels or a no BMP control scenario, but the difference in BMP performance under current and future climate was not reported numerically. Graphical representation of these data indicate that BMP performance changed little in the study watershed throughout the 21st century; the predicted changes in climate factors that could affect pollution loads and BMP performance were not reported.
- Williams et al. (2017): In a modeling study of 23 ha developed watershed in MD, with NLDAS-II forcing of several GCMs, Williams et al. (2017) used the CBP watershed model to predict increase of 12% for precipitation, 22% for streamflow, and 66% for sediment export. They determined two to three times the current levels of BMP implementation would be needed to achieve sediment TMDL given the additional ~15-30% loading under current implementation levels predicted with climate change. Additionally, they assumed climate change would increase BMP efficiency by 30%, which if not realized would indicate additional treatment needs.
- Woznicki and Nejadhashemi (2011): This SWAT study demonstrated that the performance of most agricultural BMPs is sensitive to climate change, and practices whose function is dependent on vegetation (here native grass, grazing management, and filter strips) were the most sensitive. Though no-tillage and conservation tillage are affected by the biological processes decomposing crop residues and cycling nutrients within the soil, they were much less sensitive to climate, as was the purely physical practice of porous gully plugs. Conversion of cropland to native grass was by far the most sensitive practice, and it’s sensitivity dramatically increased in future climate conditions. BMP sensitivity was also found to vary seasonally; in the case of no-tillage in the same pattern across historical and future climate, but in the case of conservation tillage,

spring variability was increased relative to historic conditions. Conservation tillage was highlighted as the most effective BMP evaluated for sediment and nutrient reductions and was also found to be relatively insensitive to climate change.

- Xu et al. (2019): The cost of attaining TMDL water quality goals under historical and future climate conditions was compared between targeting critical source areas of the watershed by topographic index and uniform implementation of BMPs. In the 7.3 km2 WE-38 subwatershed of Mahantagno Watershed, PA within the Chesapeake Bay watershed, using SWAT-VSA determined that targeting reduced BMP costs by 30% and 37% under historical and future climate, as projected from the mean output of the CRCM and WRFG climate models.

Management recommendations of simulation studies:

- Bosch et al. (2014a): highlighted differing pollutant export responses to climate change in the four sub-basins they studied as requiring different management approaches and targeting different watersheds with different BMPs.
- Chiang et al. (2012): Different BMP combinations best addressed N, P, or sediment, so treatment of the pollutant most exacerbated by climate change–sediment in this study and several other of the other watershed simulation studies–must be prioritized.
- Park et al. (2014): Seasonal changes in pollutant loads under future climate should be considered when selecting BMPs.
- Qiu et al. (2020): Since increased precipitation volume and intensity can decrease BMP efficiency, optimizing BMP application with respect to type, quantity/application intensity, and location becomes that much more important; optimal BMP selection in this case study differed between current and future climate conditions.
- Renkenberger et al. (2017): In addition to increasing the extent of critical source areas, future climate was predicted to expand hotspots for single pollutants to multiple pollutants. Therefore, BMPs originally selected to prioritize and treat single pollutants would need to be modified or supplemented with additional practices to better address sediment, N, and P simultaneously. In some watersheds, due to the increase in nonpoint source pollutant loads under future climate conditions, even natural areas may require mitigation. Therefore a “stepped-approach” to implementation is recommended, targeting hotspots for all three constituents, followed by hotspots for two constituents, etc. Theoretical BMP reduction efficiencies required to mitigate increased pollutant loads may be very high, upwards of 70-90%. The authors emphasize that while reliably removing such a high proportion of nonpoint source pollutants is a technical problem, treating such a large portion of the watershed is a social problem.
- Schmidt et al. (2019): Wider yet targeted implementation, resizing, and combining practices will be necessary. Schmidt et al. (2019) emphasize the advantages of nonstructural, annual BMPs such as no-till and cover crops, and provide the example

that cover crop species can be changed in response to local climate. They state future research on the combined effect of multiple BMPs is needed, citing the example of this and other studies modeling increased N export with N-fixing cover crops without accounting for the potential for subsequent reduction in N fertilizer application. Nutrient management, particularly the core correct rate at the correct time will be essential under any climate.

- Wagena and Easton (2018) Wagena and Easton 2018: Future strategies will need to include retrofitting or designing new practices to treat larger rainfall/runoff events effectively, developing new practices, and using multiple practices in concert.

- Woznicki and Nejadhashemi (2014): Recognize increased BMP uncertainty is expected under climate change in addition to changes in average removal efficiencies as well as the potential tradeoffs presented by the correlation with performance and variability (e.g., increased risk of underperformance with increased average effectiveness).

Application and Examples

Taking the example of cover crops, we step through a conceptual model of how climate change can impact BMP performance. Site conditions mediated by land use and land management are affected by climate change, especially more certain 'shifts', like increasing the length of the growing season. Land managers may respond by cultivating different crops or selecting different cover crops. The pollution reduction achieved by the cover crop is affected by both direct climate impacts (increased temperature and CO_2 concentration increases crop growth (Schmidt et al. 2019)) and indirect impacts manifest as stochastic weather conditions (changes in precipitation timing and magnitude also affect plant growth, especially at establishment). The ability of the cover crop to hold soil in place and take up nutrients is affected by its overall health (life stage, density, etc.) as well as the availability of nutrients in the root zone as mediated by the microbial consortium, soil moisture, and partitioning of nutrients between surface runoff and groundwater leaching. Increased precipitation can increase runoff generation, causing cover crops to be less effective with respect to N, P, and sediment retention. Climate change also affects soils nutrient cycling processes in several ways, and effects can differ depending on the pollutant. Warmer, wetter winters and springs along with increased soil moisture can increase organic P mineralization and export while simultaneously increasing denitrification and reducing N export. Increased plant growth can increase soil carbon levels, altering nutrient cycling by increasing the C:N ratio and the ratio of organic to inorganic nutrients. Improved soil structure due to the increased soil carbon content can reduce nutrient losses with surface runoff but increase losses via leaching, or reduce losses due to leaching for smaller precipitation events due to increased water holding capacity. Another contradictory effect of cover crops is potential increased nutrient uptake with faster growth and climate change also supplying increased nutrient release from this temporary biomass storage pool. In sum, cover crops appear to be highly sensitive to climate change, and given the uncertainty in climate change projections combined with the uncertainty in cover crop response, predicting how the BMP will perform is highly uncertain. However, as an annual practice it is also highly adaptable.

Predicting the changes in site condition as a result of human decision-making, even when understood through an economic lens , adds another layer of complexity and uncertainty.

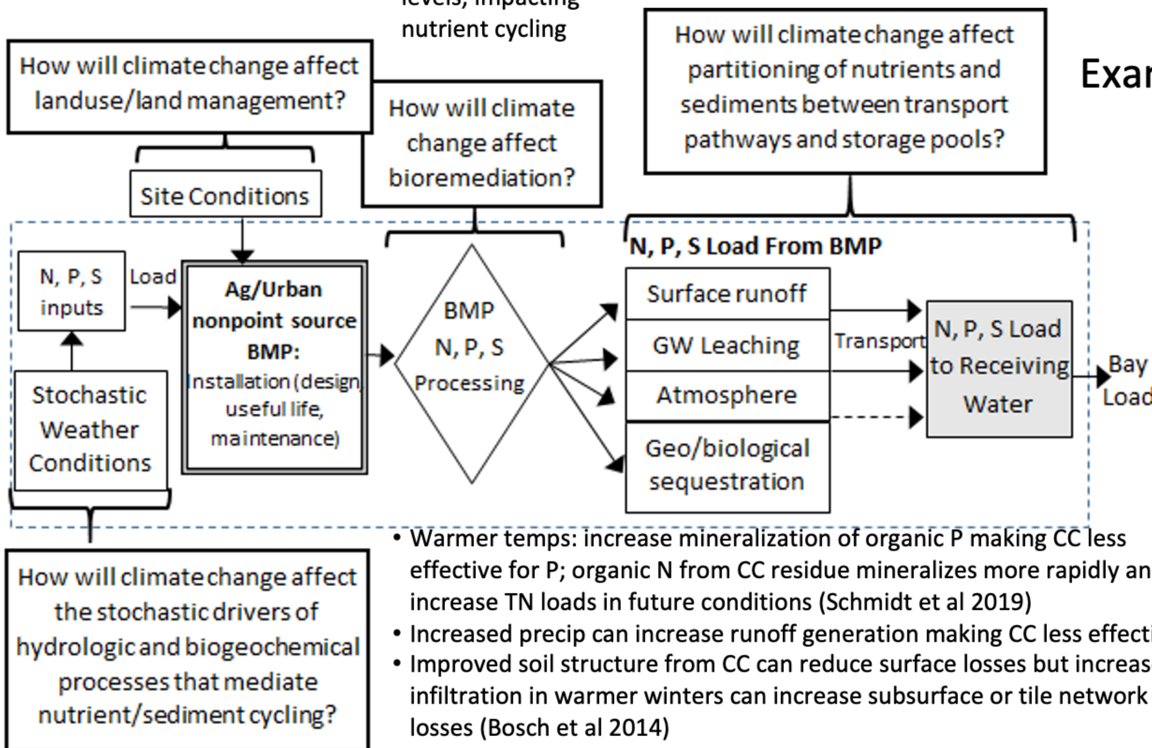
Stochastic weather conditions, such as storm duration and intensity, will affect sediment transport as well as the nutrient load and its partitioning between surface runoff and groundwater leaching.

Example BMP: **Cover Crops (CC)**

- Increased temps and CO2 can increase crop growth
- Changes in precipitation timing and magnitude also affect growth, esp. at establishment

- Increased plant growth can increase soil retention (Schmidt et al 2019) and soil C levels, impacting nutrient cycling

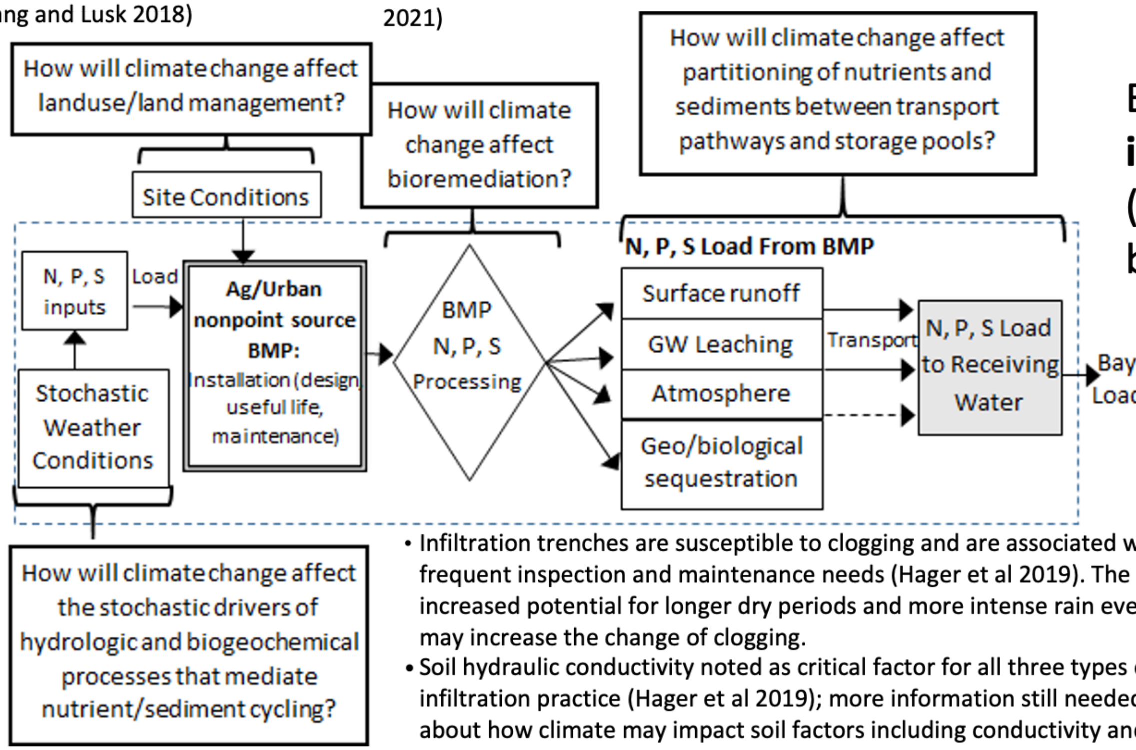
- CC may increase the ratio of organic/inorganic nutrients
- Increased plant uptake of nutrients (temporary storage pool, may be released later)
- Increased denitrification (permanent removal)



- Warmer temps: increase mineralization of organic P making CC less effective for P; organic N from CC residue mineralizes more rapidly and can increase TN loads in future conditions (Schmidt et al 2019)
- Increased precip can increase runoff generation making CC less effective
- Improved soil structure from CC can reduce surface losses but increased infiltration in warmer winters can increase subsurface or tile network losses (Bosch et al 2014)
- Irrigation and fertilization of winter CC can exacerbate TN export under future climate conditions (Schmidt et al 2019)

- Differences in buildup of N and P in urban environments; N more easily washed off by low-intensity events; P more limited in fine particles, which means that longer dry periods increase P buildup. (Yang and Lusk 2018)
- Nitrate removal by grass swales is highly sensitive to climate conditions; increasing swale length can increase nitrate removal (Valenca et al 2021)
- Vegetation in bioswales and filter strips plays major role in pollutant removal for those practices (Hager et al 2019); vegetation may see improved growing conditions under climate change.

BMP: **stormwater infiltration practices** (infiltration trench or basin; bioswale; filter strip)

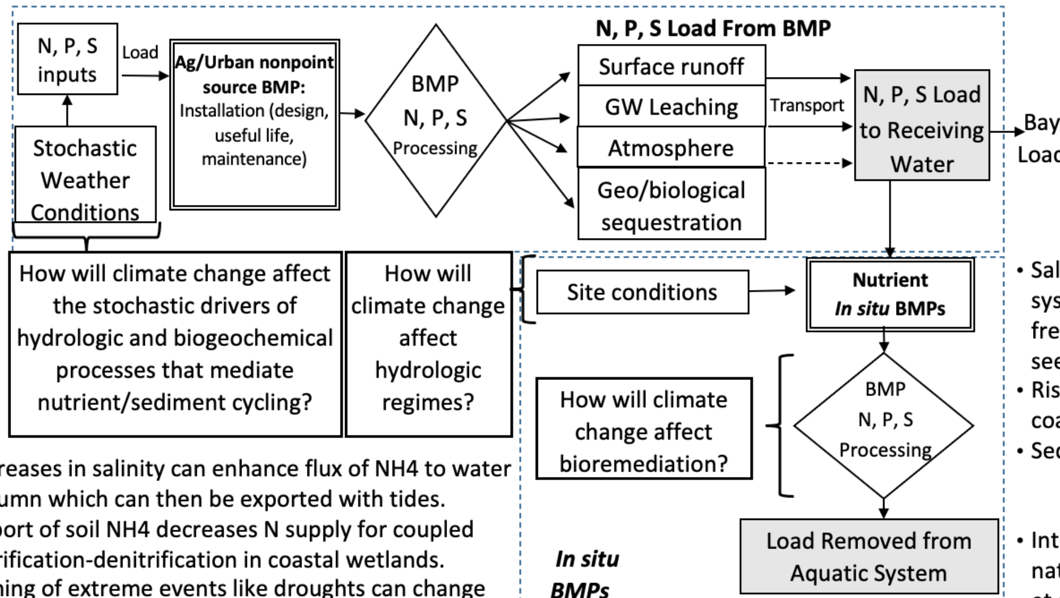


- Infiltration trenches are susceptible to clogging and are associated with frequent inspection and maintenance needs (Hager et al 2019). The increased potential for longer dry periods and more intense rain events may increase the change of clogging.
- Soil hydraulic conductivity noted as critical factor for all three types of infiltration practice (Hager et al 2019); more information still needed about how climate may impact soil factors including conductivity and soil moisture.

- Upland watershed and shoreline management can impact sediment quality and availability for tidal marsh – how might CC impact these processes?
- Restoring tidal hydrology may enable salt ions to travel farther inland than expected if only focused on SO4; prior agricultural land use exposed to low levels of salinity can release ammonium for long periods of time (Ardon et al 2013)

- Increased temps and CO2 affect growth of marsh vegetation (greater N uptake and temporary storage)
- What role does evolving balance of freshwater inputs play? (increased precip. increased streamflow) - no lit found to answer this
- What does the literature say about changes to soil chemistry and biogeochemical functions? Short answer: it's complicated and varies by wetland type, site factors

Example BMP: **Tidal wetland restoration**



- Saltwater incursion into historically freshwater wetland systems will impact microbial communities; restoring freshwater may not fully restore microbial function but can see some sensitive improvements (Huang et al 2021)
- Rising sea levels and increased storm surge can threaten coastal wetland systems
- Sediment accretion influenced by many factors
  - Liu et al 2021 suggests sediment availability is driver for success of coastal wetland restoration
- Interaction with nature-based options (living shorelines) or natural barriers (oyster reefs) can slow marsh retreat (Ridge et al 2017)

- Increases in salinity can enhance flux of NH4 to water column which can then be exported with tides. Export of soil NH4 decreases N supply for coupled nitrification-denitrification in coastal wetlands.
- Timing of extreme events like droughts can change form of exported N

Figure 23. Application of the conceptual model of climate impacts on BMP performance for cover crops (A), stormwater infiltration practices (B), and tidal wetland restoration (C).

Categorizing practices according to pollutant-reducing mechanisms

BMPs use a variety of mechanisms and processes to reduce, capture, transform, or otherwise remove nutrients or sediment. To look at a large cross-section of BMPs it is necessary to simplify or group these mechanisms within a conceptual framework such as the one described in this section and illustrated in Figure 23.

There are a number of caveats to this approach. First and foremost, the representation of BMPs within this framework is not a characterization of their ultimate resilience under a future climate, nor is it an attempt to represent the value of these practices in any terms, whether it is their water quality, environmental, social or any other explicit or intrinsic value. Indeed, many practices offer desirable habitat or other benefits that communities may find more desirable than any corresponding changes to nutrient or sediment loads. This exercise is simply an attempt to organize an understanding of complexity and potential uncertainties; this should not be interpreted as a definitive statement of these practices' expected resilience or performance under a future climate. The literature review makes it quite clear that BMP-site-specific conditions force a great deal of variability into most BMPs' performance, even under historical climate conditions. This variability will remain and likely be exacerbated by climate change, and this conceptual model seeks to flatten a lot of this uncertainty for the sake of deriving a framework that serves as a basis for continued discussion and improvement.

The mechanisms and processes by which BMPs reduce nutrient and sediment loads are divided into three categories: Biological or chemical (A), hydrological (B), and mechanical (C). Biological or chemical includes an array of processes, notably plant uptake and soil denitrification, but also other processes that are usually associated with vegetation (e.g., physical trapping) or soils (e.g., physiochemical sorption and microbially-mediated nutrient cycling processes). The hydrological category generally includes mechanisms that rely on diversion, capture or infiltration of water and thereby reduce or redirect nutrients or sediment through those processes. Mechanical is a very diverse group, with the basic connection that each of these practices generally involves the intentional collection and removal of pollutants (manure transport), reduced inputs of those pollutants (core nutrient management, precision dairy feeding), or the forced relocation or prevention of those pollutants within the landscape (stream fencing). All of these categories include both annual and structural multi-year practices. Additionally, there are many practices that utilize a combination of these mechanisms and thus fall in between A, B, or C, into the overlapping areas numbered 1-4.

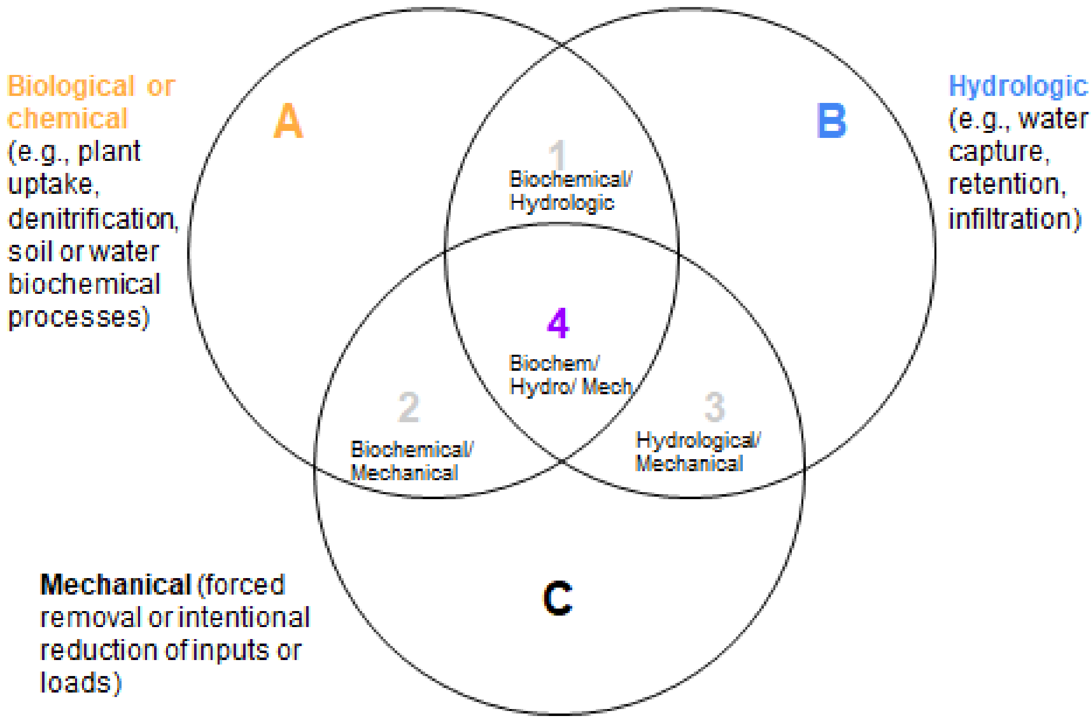


Figure 24. Conceptual model of BMP categorization based on mechanisms and processes used to reduce, remove or transform nutrients or sediment

The CBP has too many individual approved BMPs to assign each one to an area of the diagram. For this exercise some BMPs are aggregated for practical purposes (Table 11). For example, in CAST there are 100+ versions of cover crops, and several versions of forest buffers, but here we simply consider both as single BMPs.

In some cases the different versions of a BMP are explicitly separated. For instance, the CBP defines core agricultural nutrient management as the application of nutrients at rates recommended by land grant universities. This version of the BMP is placed in zone C, as the direct control of nutrient inputs is not expected to be as impacted by future climate factors. In contrast, a comprehensive "Four R" approach - right source, right rate, right time and right place - consistent with the CBP's supplemental agricultural nutrient management BMPs, intersects with the other zones (A and B) in more complex ways.

Table 11. Initial classification of certain BMPs to areas of the venn diagram conceptual model

BMP or BMP group	Best approx. assignment
Ag Nutrient Management	4 or C (rate/core only)
Tillage Management	B
Cover Crops	1 or A
Urban Nutrient Management	4
Pasture Management	1
Forest Harvesting	B
Manure Incorporation	1 or B
Land Retirement	1 or 4
Wetland Rehabilitation	A or B
Tree Planting	A
Grass Buffers	1
Forest Buffers	1
Animal Waste Management Systems (AWMS)	C
Stream restoration	1
Wet ponds and wetlands	1
Tidal wetland restoration	1
Nontidal wetland restoration	1
Living shoreline	1
Oyster restoration or aquaculture	2
Bioretention	1
Erosion & Sediment Control (construction)	B
Dry ponds	B
Rooftop or imp. disconnection	B
Barnyard runoff control	B
Denitrifying bioreactors	3 or 4
Algal flow-ways	2
Stream fencing	C
Street sweeping	C
Manure treatment	C
Manure transport	C
Constructed wetland	4
Drainage water management	B

Certain BMPs are more difficult to assign in one area, even in this subjective diagram (Figure 25), and may be listed in more than one place, such as cover crops and wetland rehabilitation (Table 11). Wetland rehabilitation can address multiple factors within a degraded wetland, and could also therefore fall into zone 1. For now, it is placed in both A and B, to reflect rehabilitation projects that target vegetation or soils-based problems (A), or hydrology (B). In contrast, we place wetland restoration in zone 1. Though wetland restoration can sometimes be done by restoring the hydrology, the wetland still functions through a combination of biochemical and hydrologic factors. , though it can sometimes be achieved through "constructed wetlands" listed in zone 4.

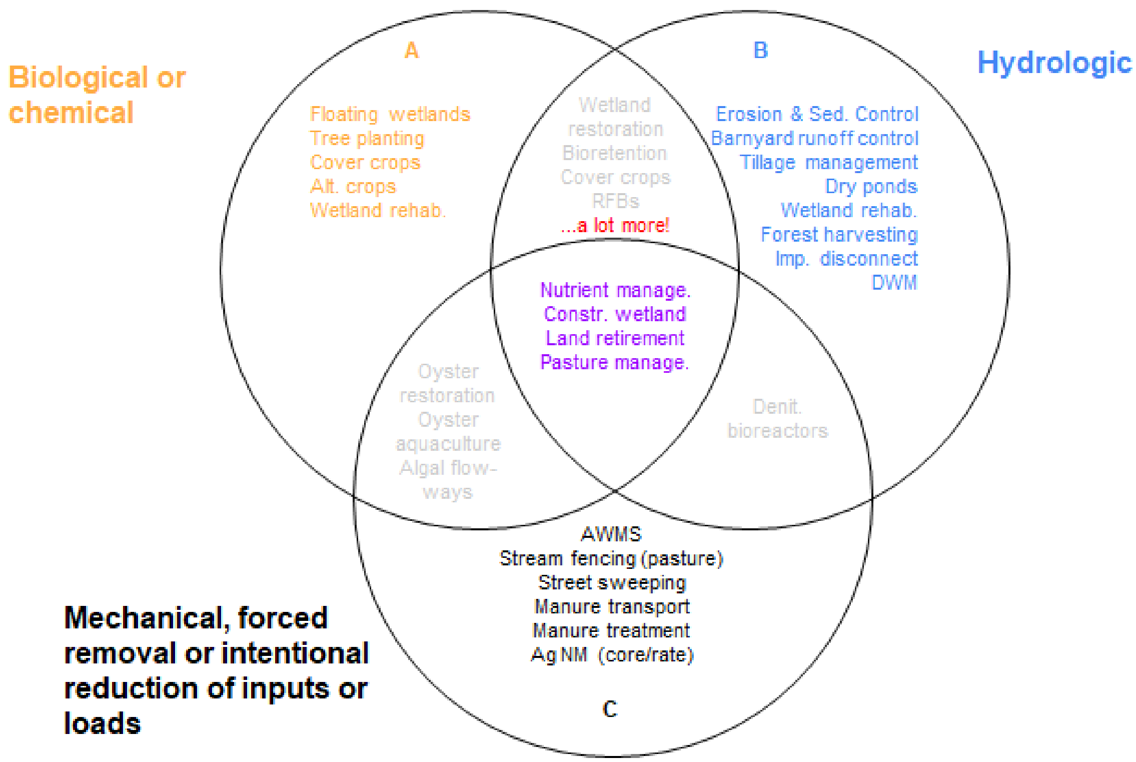


Figure 25. Conceptual model with preliminary allocation of certain BMPs

The more complex, nature-based practices may be associated with relatively greater variability and uncertainty, but this is largely due to a lack of current knowledge and does not reflect on the benefits of those practices. Indeed, many of these same nature-based practices may have greater resilience due to competing or overlapping processes that exist in complex natural systems. This complexity greatly complicates attempts to understand potential changes in their water quality effectiveness in a changing climate, but this complexity can create redundancies and resilience.

While the practices in Zone C may, on average, be less likely to be heavily affected by climate change impacts, it does not make them immune. For example, consider street sweeping. The BMP expert panel for this practice pointed out that the sediment and nutrient benefits of the practice are modest, even under the most frequent sweeping scenarios. The use of more advanced sweepers (vacuum-assisted or regenerative air) increases the pollutant removal of these practices, but the benefit is largely dependent on the sweeping frequency in order to collect the street sediments prior to wash-off by a storm (Donner et al. 2016) (Donner et al. 2016). While we found no modeling or empirical studies of street sweeping effectiveness in a future climate, the expectation of more frequent and larger storms suggests that street sweeping could be heavily impacted by climate change.

While this exercise attempts to isolate individual practices in an abstract sense, BMPs are rarely implemented in isolation in the real world. Any given catchment or watershed in the region is likely to have an array of practices that already exist in the landscape, and there are likely to be new practices installed in the future in addition to recurring annual practices or maintenance of existing structural practices. Therefore, it is important to consider that BMPs have the potential to reinforce other practices within the same immediate environment. The fact that there is already such widespread implementation of BMPs emphasizes the need for BMP verification to ensure practices continue to function, and reinforce one another, as intended.

Characterization of Factors Influencing BMP Performance Risk Under Future Climate

The literature reviewed for this project allows a characterization of key factors that affect BMPs' performance. When key factors overlap with expected climate impacts such as those described in the Q1 section, it suggests that the BMP's performance is at some level of risk under a future climate.

How is risk and uncertainty of BMP performance under a future climate distinct from risk and uncertainty of a BMP under current or past conditions

There is always a level of uncertainty as well as natural variability when considering the nutrient and sediment effectiveness of an individual BMP project or a class of BMPs. The varying performance can be due to knowable site factors or intentional design choices as well as due to unknown or unforeseeable factors. It can result from a lack of maintenance or operational knowledge, or it can be due to stochastic, outside events. In other words, some variability could be controlled, but even in the best circumstances there will be variability in BMP performance. Uncertainty can be reduced in specific circumstances as knowledge and awareness increase, but it can never be eliminated, especially in complex open systems where most BMPs function.

As noted in the Q1 section, this project seeks to understand how changes in climate may affect BMP performance. So, while each BMP and each mechanism that contributes to a BMP's ability to reduce nutrient or sediment loads has uncertainty and variability associated with it, the focus here is identifying where and/or how that uncertainty overlaps with changing climate factors or other expected climate change impacts. While it may be difficult to draw meaningful conclusions about the extent to which BMP uncertainty might change, an improved understanding of these intersections can serve as a basis for future researchers to elucidate greater insights. In other words, even though we often do not know much about the probability function for a BMP's performance, it is still possible to identify the factors that are likely to influence the shape or other characteristics of that probability distribution (e.g., central tendency) under a future climate.

For purposes here, risk is considered based on possible outcomes in spite of the BMP performance uncertainty noted above. This may differ from accepted distinctions of risk and uncertainty, where risk is defined by situations with an unknown outcome, but known probabilities, and; where uncertainty is characterized by an unknown outcome and an unknown probability distribution (Knight 1921; De Groot and Thurik 2018). For this report, it is accepted that there will always be uncertainty of both the outcome (i.e., BMP performance) and the underlying probability function that is based on a range of environmental and human factors. However, it is useful to apply the term risk and distinguish it from uncertainty based on a spectrum of possible outcomes of interest for a BMP or class of BMPs, including diminished performance or outright failure. Figure 26 is a useful spectrum of risk that considers such outcomes. It was adapted from a similar spectrum described in (Wood 2021) that was generated by that author to consider risk for stormwater BMPs. For purposes here, some additional options and changes to descriptions were incorporated.

One additional outcome to the risk spectrum for the current context, is the possibility of "no predicted change based on current information." This reflects a situation where a practice's key mechanisms may be associated with climate impacts, but there is not enough information to indicate if the practice should be linked to one of the options in the risk spectrum. Similarly, there is a need for an "unknown" option on the risk spectrum. This option applies in cases where a BMP's and its mechanisms are not well understood or studied, and the connections to climate impacts are also unclear.

Some practices have relatively little risk, given the factors that influence their performance or load reductions. For these instances, the outcome of "relatively little risk" is added to the spectrum. Note that "relatively little risk" is not zero risk, and this is not intended to convey a value judgment on the BMP compared to other BMPs. It merely suggests that based on what is understood about how the BMP functions that expected climate impacts are relatively less likely to influence the BMP's ability to reduce nitrogen, phosphorus or sediment loads to the Bay.

Most or any individual BMPs can fail due to a variety of chronic or acute factors, and that failure may not be preventable or predictable. Climate change may alter the probability of complete failure due to overwhelming individual storm events, or perhaps due to slower processes such as sea level rise. However, the focus for this cross-sector report is more about performance and less about resource or infrastructure impacts associated with "catastrophic failure," so the risk spectrum for the current context will exclude that potential outcome. However, the structural and anticipated failure options are still applicable for purposes here.

Finally, the focus for this project is for water quality. Therefore, the outcome of "water quantity performance failure" is omitted from the spectrum for simplicity. However, we will indicate when a practice is necessary for other Chesapeake Watershed Agreement goals or outcomes...

In summary, the final set of possible options for BMPs based on climate-induced risk are as follows (Figure 26):

- Structural failure
- Water Quality performance failure (WQ performance failure)
- Diminishing performance
- Anticipated failure
- No predicted change based on current information
- Unknown
- Relatively little risk

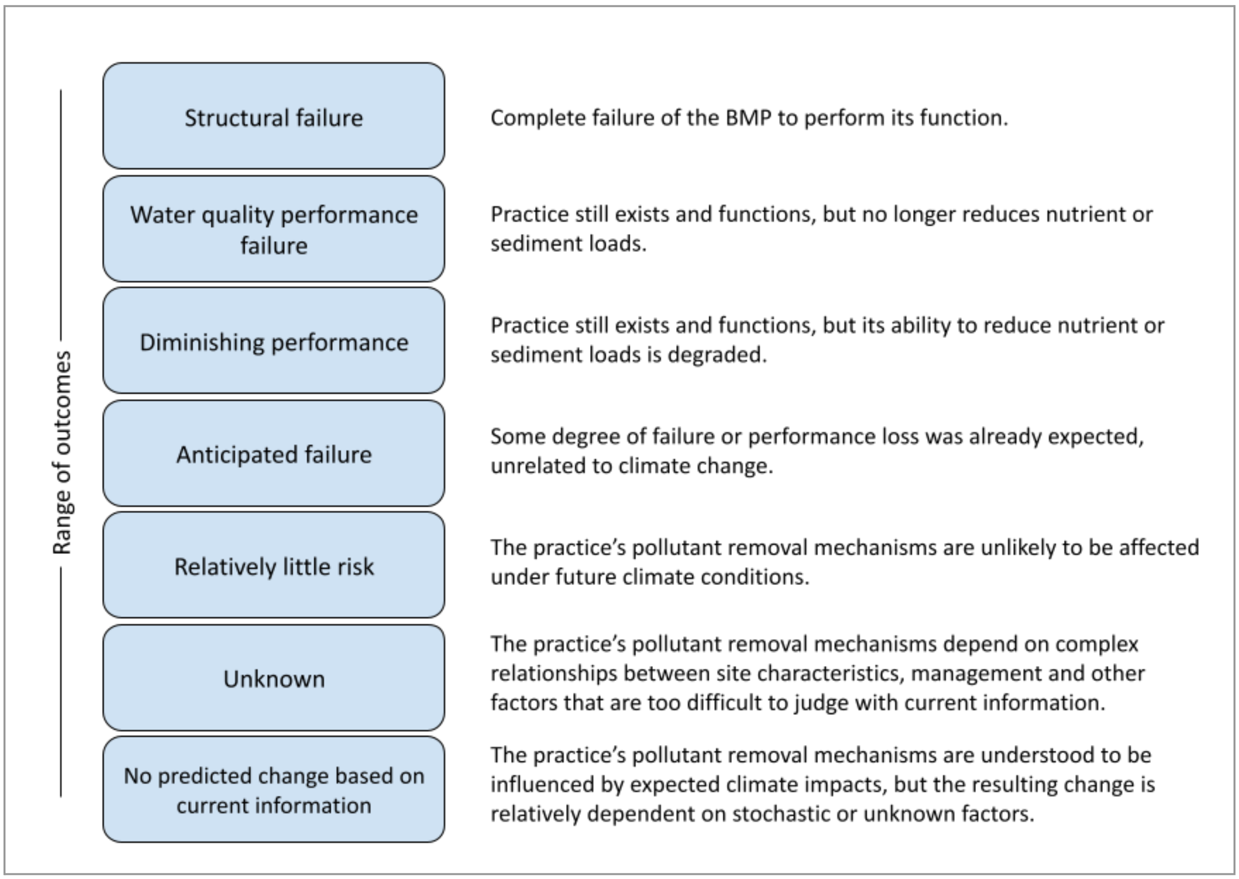


Figure 26. Spectrum of possible options for BMPs associated with climate factors

To recap, the BMP performance and mechanism conceptual model (Figure 25) and characterization of climate-induced risk (Figure 26) build on one another, and in turn enable early attempts to identify and describe logical interventions.

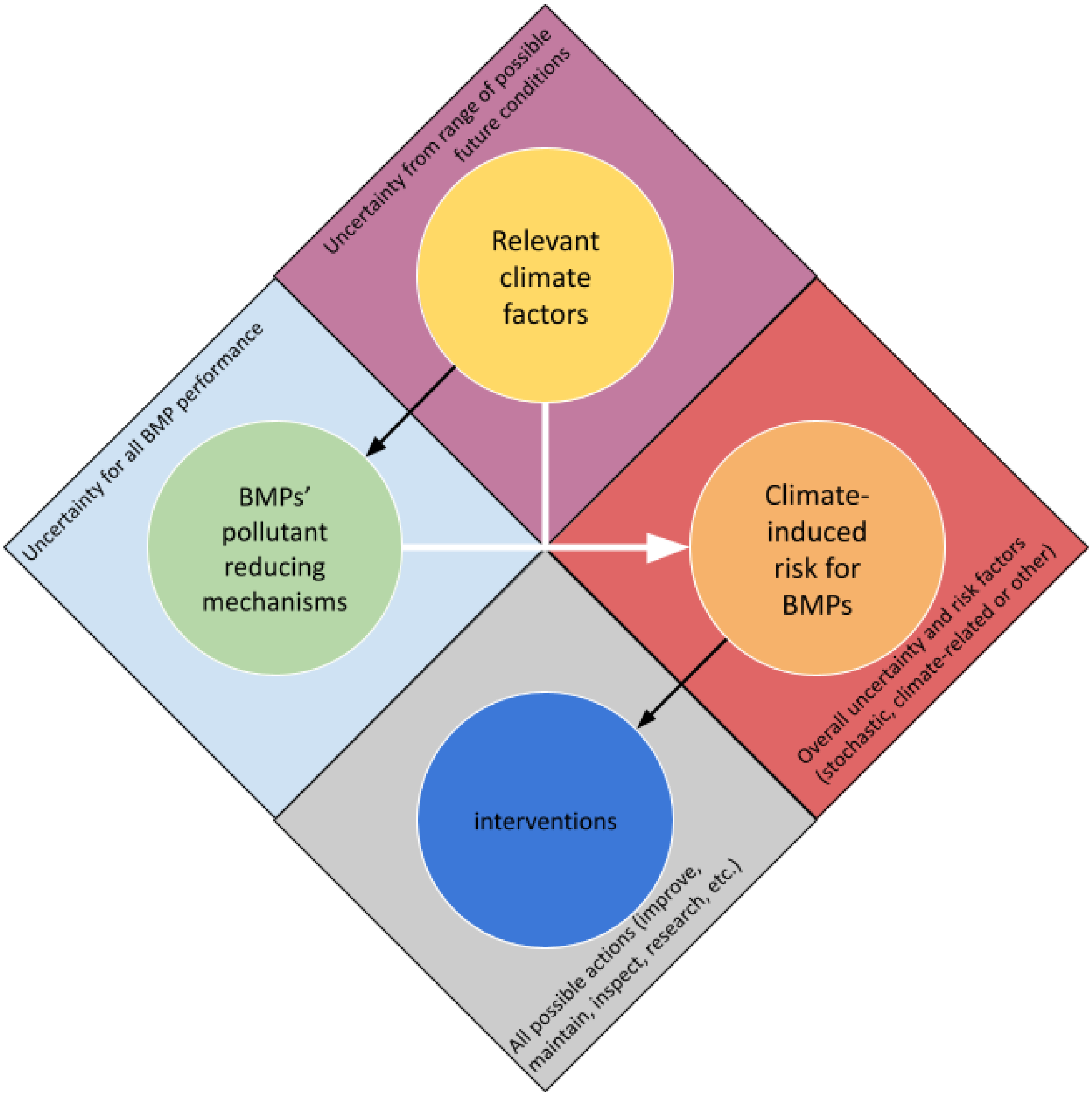


Figure 27. Flow of concepts in this narrative: Relevant climate factors are detailed in the Question 1 section; we seek to understand how those climate factors influence BMPs' pollutant-reducing mechanisms. Both concepts combined influence how we interpret risk and uncertainty regarding BMP nutrient and sediment performance and thereby inform possible interventions or adaptive management strategies.

Putting all of the information together in one place is a challenge. To do this in a manageable way, Tables 12 - 15 combine the following information for each BMP listed in Column 1:

Column 2: The preliminary categorization based on the venn diagram model in Figure 24 and Figure 25 and the BMP's primary mechanisms/processes

Column 3: Key performance factors, i.e., "BMP performance primarily depends on…"

- BMP performance can be highly variable and often varies based on site conditions, operations and maintenance, or many other factors. For this table, the factors listed are the ones judged here to be the most important or most relevant to a BMP's performance in either historical or future climate conditions.

    - For example, the street sweeping expert panel notes that the adoption of parking controls can improve the effectiveness of street sweeping, but we do not list that factor here given the larger effect from the sweeper technology and frequency of sweeping. Granted, in areas where parked cars block a sweeper's access to the curb and gutter it can theoretically reduce the sweeper's effectiveness to almost zero for that area. However, these kinds of contextual factors are generally assumed to be less impactful than factors that would alter the overall implementation of that practice. In other words, upgrades to frequency of sweeping or sweeper

- It is acknowledged that BMP performance depends on a large number of factors. For purposes here, it is not practical to exhaustively list all factors, so a judgment is made about which factors are most relevant to the BMP's performance when considering past or future climate.
- The performance of some BMPs is directly related to the management action or structure itself, such as manure transport. There may be some negligible differences in how the action is conducted or how the structure is installed, but overall there is little expected influence from climate factors to the performance of such practices.

Column 4: Relevant climate factors influencing BMP performance.

- What aspects of climate change are most critical to understand to assess BMP performance.
- Relevant climate factors include precipitation volume, timing, variability, and intensity; minimum, maximum, average temperature and variability; changes to atmospheric CO_2 concentrations; solar radiation; potential evapotranspiration.

Column 5: An initial characterization of climate-induced risk, i.e., "Expected risks under future climate"

- This column primarily builds on the spectrum described by (Wood 2021), which is broadened for purposes here to conceptually accommodate other sectors (Figure 26). The expected outcomes are based on performance factors in the preceding column when combined with expected climate impacts.
    - For example, consider street sweeping. The frequency of precipitation events is expected to increase, along with intensity, which will decrease the window of time for street sweepers to collect street dirt or detritus prior to washing off into the storm drain system. This represents the potential for a "water quality performance failure" or "diminishing performance" under the risk spectrum, as the practice will still perform some intended functions, but may no longer perform pollutant removal, or a diminished rate of pollutant removal.

Column 6: potential adaptive management actions, i.e., "Interventions" or "adaptations" as in Figure 26 and Figure 27.

- If the literature identifies promising actions, changes, or improvements that can potentially improve or maintain performance of a BMP into the future, these actions are briefly noted here. Our focus is more general for a given practice or set of practices, so while we try to synthesize actions that can apply to the practice broadly - for example, upgrading the type of street sweeper used or the frequency of sweeping - we otherwise omit specific criteria or guidance in favor of generic interventions.

- Inspect & maintain
- Monitor
- Research
- Update designs

Table 12. Summary of BMPs' key performance, relevant climate factors, expected risks under future climate and initial identification of possible interventions or adaptations; BMPs with primarily mechanical or forced pollutant removal/prevention (Area C from Figures 24-25).

BMP or BMP group	**Best approx. assignment**	**BMP performance depends on**	**Relevant Climate Factors**	**Expected risks under future climate**	**Possible interventions/ adaptations**
Ag Nutrient Management (core)	C	For core: Following prescribed rate from NM plan	Increased precipitation volume and intensity and temperatures	Diminishing performance from increased runoff and leaching	Research, update 4R's recommendations
Animal Waste Management Systems (AWMS)	C	Storage structure; animal type; management	Increased precipitation intensity; precipitation variability	Structural failure from increased precipitation volume	Monitor, for failure; Research, update systems for larger return period storms, improve separation technology
Stream fencing	C	The structure itself	Increased precipitation volume and intensity	Structural failure from streambank erosion	Monitor for function; Research, update and improve designs
Street sweeping	C	The type of sweeper, frequency	Increased precipitation volume and intensity	WQ performance failure; diminishing performance from increased precipitation frequency and intensity	Research, Upgrade sweeper technology, increase frequency of sweeping
Manure treatment	C	The type of treatment technology	NA[1]	Relatively little risk	Monitor, for emissions; Research, develop new conversion technologies
Manure transport	C	The act itself	NA	Relatively little risk	NA

[1] Emissions regulations may change the expected climate risk for manure treatment technologies.

Table 13. Summary of BMPs' key performance, relevant climate factors, expected risks under future climate and initial identification of possible interventions or adaptations; BMPs with primarily biological or geochemical pollutant removal/prevention (Area A from Figures 24-25).

BMP or BMP group	Best approx. assignment	BMP performance depends on	Relevant Climate Factors	Expected risks under future climate	Possible interventions/ adaptations
Cover Crops	1 or A	Crop species or mixture; planting date and method, establishment	Precipitation variability/intensity; altered growing season; Increased temps and CO_2	Diminishing performance from increased variability, but countered by increased plant biomass from CO_2 effect[1]	Research, improve species selection, timing, planting recommendations
Wetland Rehabilitation	A or B (or 1)	Landscape position, design, complex factors, time	Precipitation variability/intensity; Increased temps and CO_2	Diminishing performance from increased water balance but countered by increased plant biomass from CO_2 effect[1]	Monitor, inspect and maintain; Research, update designs and recommendations, develop more adapted species
Tree Planting	A	Planting density and survival, upkeep or maintenance	Precipitation variability/intensity; altered growing season; Increased temps and CO_2	Diminishing performance from increased variability but countered by increased plant biomass from CO_2 effect[1]	Monitor, for establishment; Research, develop more adapted species, update recommendations

[1] Although evidence exists that many of these natural type BMPs may function better under higher temperatures and CO_2 concentrations as long as moisture is not limiting (this also depends on plant type, C3 or C4 species).

Table 14. Summary of BMPs' key performance, relevant climate factors, expected risks under future climate and initial identification of possible interventions or adaptations; BMPs with primarily hydrological-based pollutant removal/capture/prevention (Area B in Figures 24-25).

BMP or BMP group	**Best approx. assignment**	**BMP performance depends on**	**Relevant Climate Factors**	**Expected risks under future climate**	**Possible interventions/ adaptations**
Tillage Management	B	Crop residue coverage, level of disturbance	Precipitation variability/intensity	Diminishing performance from increased precipitation intensity	Research, new tillage practices
Forest Harvesting	B	Level of disturbance	Precipitation; Increased temps and CO_2	Relatively little risk	Research, update & improve design
Manure Incorporation	1 or B	Injector type; level of disturbance; timing	Precipitation variability/volume,Increased temps	Diminishing performance from greater runoff	Monitor, for WQ benefit; Research, update design, new manure incorporation technology
Erosion & Sediment Control	B	Stabilization of site; maintenance of practices	Precipitation intensity	Diminishing performance from increased precipitation intensity	Monitor, for failure; Research, update design, new IDF curves
Dry ponds	B	Antecedent conditions;	Precipitation intensity	Diminishing performance from increased precipitation intensity	Monitor, for failure; Research, update design, new IDF curves
Rooftop or imp. disconnection	B	Physical infrastructure itself	Precipitation volume/intensity	Relatively little risk, hydraulic failure could occur	Research, update design, new IDF curves
Barnyard runoff control	B	Physical infrastructure itself	Precipitation volume/intensity	Relatively little risk, hydraulic failure could occur	Monitor, for function; Research, update design, new IDF curves
Drainage	B	Antecedent	Precipitation	Relatively little risk, hydraulic	Monitor, for function;

water management		conditions; infrastructure	volume/ variability	failure could occur	Research, update designs, new drainage practices

Table 15. Summary of BMPs' key performance, relevant climate factors, expected risks under future climate and initial identification of possible interventions or adaptations; BMPs with blended or multiple types of pollutant removal mechanisms (Areas 1, 2, 3 or 4 in Figures 24-25)

BMP or BMP group	**Best assignment**	**BMP performance depends on**	**Relevant Climate Factors**	**Expected risks under future climate**	**Possible interventions/ adaptations**
Ag Nutrient Management (core + supplemental)	4	Soil and crop factors	Precipitation variability/ intensity; altered growing season;	Diminishing performance from increased runoff and leaching losses	Research, improve plant nutrient use efficiency, adjust timing/frequency of nutrient applications, adjust recommendations
Urban Nutrient Management	4	Rate and timing	Precipitation variability/ intensity	Relatively little risk	Research, adjust recommendations
Pasture Management	1	The act itself (allowing regeneration between grazing periods); landscape factors (slope), and vegetation	Precipitation variability/ intensity; altered growing season; Increased temps and CO_2	Diminishing performance from increased runoff, but perhaps countered by increased plant biomass from CO_2 effect	Research, more adapted pasture species, adjust grazing management strategies
Land Retirement	1 or 4	The act itself; WQ value of the land	Precipitation variability/ intensity; altered growing season; Increased temps and CO_2	Relatively little risk	Monitor, evaluate for environmental benefit
Grass Buffers	1	Landscape position; Soil and plant factors; time	Precipitation variability/ intensity;altered growing season;	Diminishing performance from increased runoff, but perhaps countered by	Monitor, for concentrated flow path formation; Research, update establishment

			Increased temps and CO_2	increased plant biomass from CO_2 effect	recommendations, more adapted buffer species
Forest Buffers	1	Landscape position; Soil and plant factors; time	Precipitation variability/ intensity; altered growing season; Increased temps and CO_2	Diminishing performance from increased runoff, but perhaps countered by increased plant biomass from CO_2 effect	Monitor, concentrated flow path formation; Research, update establishment recommendations, more adapted buffer species
Stream restoration	1	Complex site factors	Precipitation variability/ intensity	Diminishing performance/structural failure from higher intensity storms	Monitor, for failure, for WQ benefits; Research, update recommendations
Wet ponds and wetlands	1	Landscape position, complex site factors, time	Precipitation variability/ intensity; Increased temps and CO_2	Diminishing performance/structural failure from higher intensity storms	Monitor, for failure, for WQ benefits; Research, update recommendations, employ new IDF curves
Tidal wetland restoration	1	Soil and plant factors; time	Precipitation variability/ intensity; Increased temps and CO_2 / Ocean acidification	Diminishing performance/structural failure from higher intensity storms but perhaps countered by increased plant biomass from CO_2 effect	Monitor, for WQ benefits; Research, update recommendations, employ new IDF curves, develop more adapted species
Nontidal wetland restoration	1	Landscape position, complex site factors, time	Precipitation variability/ intensity; altered growing season; Increased temps and CO_2	Diminishing performance from higher intensity storms but perhaps countered by increased plant biomass from CO_2 effect	Monitor, for WQ benefits; Research, update recommendations, employ new IDF curves, develop more adapted species
Living shoreline	1	Soil and plant factors;	Precipitation	Relatively little risk	Monitor, for performance;

		time	variability/ intensity/ Ocean acidification		Research, update recommendations
Oyster restoration or aquaculture	2	Site suitability	Increased temps and CO_2 / Ocean acidification	Relatively little risk	Monitor, for performance ; Research, update recommendations
Bioretention	1	Landscape position, complex site factors, time	Precipitation variability/intensity; Increased temps and CO_2	Diminishing performance from higher intensity storms	Monitor, for failure, for WQ benefits; Research, update recommendations, employ new IDF curves
Denitrifying bioreactors	3 or 4	Complex substrate factors	Increased temps	Relatively little risk	Monitor, for performance
Algal flow-ways	2	Site suitability	Increased temps/ Ocean acidification	Relatively little risk	Monitor, for performance
Constructed wetland	4	Landscape position, complex site factors, time	Precipitation variability/intensity; Increased temps and CO_2	Diminishing performance from higher intensity storms but perhaps countered by increased plant biomass from CO_2 effect	Monitor, for WQ benefits; Research, update recommendations, employ new IDF curves, develop more adapted species

Discussion

Discussion of Key BMPs: front-line BMPs

Some practices, including those identified for the additional review from NOAA, warrant particular consideration and may be best understood as *front-line BMPs* or *front-line practices*. Front-line BMPs can be defined by two criteria. First, they exist in physical spaces within the watershed, shoreline or estuary where the impacts of climate change are virtually certain to manifest, whether through high sensitivity to acute weather events (flash floods, droughts, large storms) or chronic changes over time to historic baselines (sea level rise, acidification). Second, these BMPs are often heavily relied upon to achieve environmental goals or outcomes - not only water quality - or they themselves are the metric, or an explicit part of a measured outcome. This is because they exist as a key environmental nexus and/or serve as critical habitat hot-spots. Practices that meet both of these criteria can accurately be described as front-line BMPs: they are not only keenly exposed to climate change, but also play a critical role in mitigating or adapting to its impacts for water quality or other purposes. Practices that meet both criteria and can be considered as such front-line practices: living shoreline, oyster restoration or aquaculture, non-tidal and tidal wetland restoration, forest buffers, and stream restoration.

Relatively few studies found in this systematic review discuss oyster practices and living shorelines, though considerations of living shoreline overlaps with some of the tidal wetland literature; for example, with respect to sediment dynamics in the nearshore estuarine environment.

Regarding oysters and oyster BMPs, estuarine climate factors such as changes in water chemistry (salinity, pH, temperature) and sea level rise are of the greatest concern. This discussion draws mostly on two studies Miller et al. (2017) and Ridge et al. (2017) . The forthcoming BMP expert panel report for oyster restoration is expected to have more relevant information than was available in the third study by Caffrey et al. (2016). In the case of Miller et al. (2017), the study was concerned with how managers might improve their modeling for site selection within the Gulf of Mexico. While the purpose of site selection is not applicable for this review, those authors did offer relevant insights into factors that impact the success of oyster restoration efforts, including not only temperature and salinity, which are usually considered, but also the role of timing, duration and frequency of low salinity events, particularly when combined with higher temperatures. Increased annual or seasonal streamflow and frequency of large precipitation events could potentially compound their impact under future climate conditions to heighten stress of oyster reefs. Modelers could further investigate the range of possible climate futures for oyster reefs in areas of interest; it is likely that the information, Chesapeake Bay models and knowledge to perform this type of analysis already exist. The question of interest, to be refined by interested subject matter experts such as those within the Fisheries Goal Implementation Team, would be to what extent future climate conditions will produce periods of increased stress (multiple stressors) such as those identified by Miller et al. (2017), including low salinity for extended periods, especially at higher temperatures; the frequency, timing and duration of low salinity events; as well as increased infection risks associated with high salinity and higher temperatures.

The other oyster-related study by Ridge et al. (2017) offered interesting insights based on tidal marsh and oyster reef data from North Carolina, which suggest that strategically implementing oyster reef planting to protect marsh environments may be able to extend ecosystem functions and preserve buried carbonaceous sediments. Transferability to the Chesapeake Bay is unclear and best left for consideration of oyster and estuarine management experts, but it is one potential innovation to use natural elements to protect tidal shoreline marsh areas.

No studies were found in this review that addressed oyster aquaculture activities.

A relatively small number of studies were found in the initial systematic review for riparian forest buffers, leaving this review to focus on Sweeney and Newbold (2014). Their high-quality review of the literature through 2012 reports reductions in nitrogen, sediment and erosion; water temperature; and stream habitat suitability for macroinvertebrates and fish communities with respect to buffer width and water flux. They conclude that to protect water quality, habitat and biota in small streams buffers of at least 30 meter width are needed. They offer predictive equations for nitrate and sediment removal efficiency rates built from the literature. A targeted expansion of this analysis of available data in the published literature would be prudent for future efforts, with this article serving as a keystone.

Most of the tidal wetland literature reviewed through this study focused on sediment dynamics or processes. While these dynamics with respect to sediment accretion are certainly vital for longevity of wetlands, there was less information regarding nutrient or carbon processes.

Tidal wetland literature from the search was somewhat concentrated with studies in the Gulf of Mexico (Louisiana (Brantley et al. 2008), Mississippi (Alizad et al. 2018), Florida Everglades (Kominoski et al. 2020)) and San Francisco Bay regions (Buffington et al. 2020; Callaway et al. 2007; Cecchetti et al. 2020), though there was a wide range of locations including other eastern U.S. areas (including Connecticut (Bernhard et al. 2015; Doroski et al. 2019), Chesapeake Bay (Fleri et al. 2019) and North Carolina (Ardon et al. 2013), and estuaries in China (Huang et al. 2021). Reviews of national or global scope were also included (Leonardi et al. 2018; Liu et al. 2021).

Much of the reviewed literature revolves around changes in tidal regions, typically as a result of sea level rise or from disturbance events such as hurricanes. The transition between land cover classes - particularly from emergent wetland to open water - is of particular interest in the Chesapeake Bay region, where sediment accretion in tidal wetlands may struggle to keep pace with other forces such as sea level rise. Marsh migration is a complex process that cannot be described in depth here, but it should be noted that land cover change is occurring at accelerated rates in the region, with forest retreat estimated at multiples of pre-industrial rates in areas of Maryland and Virginia (Kirwan and Gedan 2019). One study of Somerset County land cover change within 2 km of maximum tidal extent (total study area of 625.43 km^2) over only 8 years (2009-2017) found that 16.1 km^2 transitioned to new land cover (Gedan et al. 2020). The authors found that out of the transition area, 38% started as agricultural land in 2009 and about

26% started as forest in 2009, while another 15% and 16% started as emergent wetland and scrub-shrub wetland, respectively, with the remainder starting as urban or open water. Most of the lost agricultural land transitioned to emergent wetland and about half as much went to forest, with a smaller portion of that changing to urban land (development). Notably, there was a significant extreme drought during the study period in the summer of 2011, as well as Hurricane Sandy in 2012, suggesting these disturbance events played a role. Most of the lost forest transitioned to scrub-shrub wetland or emergent wetland, while emergent wetland transitioned primarily to open water. Gedan et al. (2020) estimated that this transition represents a loss of over 2% of farmland in Somerset County in that short time period.

Given such rates of change, sediment dynamics that contribute to accretion and marsh longevity, managed retreat of marsh, and possible methods to combat effects of saltwater intrusion were common themes in the reviewed studies. The impacts and role of disturbance events such as fire, drought and hurricanes were also explored (e.g., (Kominoski et al. 2020)) or noted when they occurred during a study period. In two drainage systems within the Everglades, Kominoski et al. (2020) found increases in TN from upstream freshwater marshes following disturbance events (fire in 2008 and droughts in 2010 and 2015), while downstream TP increased with coastal storm surge from hurricanes in 2005 and 2017. Regarding sediment, Liu et al. (2021) is a key paper that encompasses living shorelines as part of the authors' definition of "nature-based solutions." They identify a site's sediment availability as a greater factor in their effectiveness than elevation, tidal range, or local sea level rise rates, among other factors, and suggest that nature-based solutions can be most effective to mitigate coastal wetland vulnerability when they have an abundant sediment supply.

As noted in Figure 23(C) the restoration of freshwater wetlands to combat saltwater incursion can improve microbial functions, in terms of increased denitrification and anammox for example, but these ecosystems appear to be sensitive and do not fully regain microbial community structure and function to previous, desired levels (Huang et al. 2021). One study found that restoring tidal hydrology may enable salt ions to infiltrate farther inland than expected if focused on sulfate alone, as sulfate did not infiltrate as far inland (Ardon et al. 2013). They also found that low levels of salinity may release ammonium for long periods of time from lands that were previously used in crop production (Ardon et al. 2013). As previously agricultural lands transition to wetland in the Chesapeake Bay, the findings from Ardon et al. (2013) may warrant careful attention from researchers in this region as a potentially significant source of nutrients. Increased denitrification rates are achievable in restored wetlands, and can increase along with time since restoration (Doroski et al. 2019), but even with decades of time restored wetland systems (both tidal and non-tidal) will struggle to approach functional levels associated with natural reference wetlands (Ballantine and Schneider 2009; Moreno-Mateos et al. 2012).

The literature search only returned one study of stream restoration, Williams et al. (2017), which also considered future climate conditions as part of their analysis. The authors conducted a field study of a restored wetland-stream complex in the Maryland Coastal Plain, as described in Table 6.

Studies reinforce the importance of protecting natural systems, features and the functions they provide (Pelletier et al. 2020). While the CBP does have methods to account for conservation actions in future planning scenarios within CAST, preservation efforts are generally accounted for programmatically such as through Watershed Agreement Outcomes. For example, allowing for migration of tidal marsh is not a CBP-approved BMP while the installation of a living shoreline is a BMP that can be simulated within CAST. However, studies such as Liu et al. (2021) consider "managed retreat" as part of the suite of nature-based actions available to managers.

Unfortunately, this review did not identify or reveal any specific thresholds for practitioners to guide management. Such thresholds would be valuable to identify when certain BMPs are no longer viable in terms of water quality or provisioning of habitat. While specific numeric thresholds were not identified, the literature may offer examples of potentially relevant indicators or warning signs in the case of some nature-based practices or natural preservation areas. Noe et al. (2021) found that shifts in the composition of the shrub and herbaceous layer can be an early indicator of conversion of tidal freshwater forested wetlands to oligohaline marsh and could be identifiable prior to the substantial decline and eventual loss of longer-lived trees. It is unclear if interventions could prevent or slow this conversion and loss of valuable longer-lived trees, but there is literature to suggest that restoring freshwater hydrology can restore microbial activities and some of the functions in wetland soils (Huang et al. 2021), at least in the short term. That is not the same thing as saving longer-lived trees, but it at least offers a potential stalling tactic that could allow managers to implement additional actions that could include managed retreat or other restoration activities.

Even though the literature search and review was carefully phrased to identify studies that targeted these kinds of "front-line BMPs" the results were less insightful overall than desired and heavily skewed in favor of tidal wetlands. Targeted literature reviews built from highly relevant key papers would be more likely to yield a rich body of relevant literature in the case of riparian buffers and oysters in the future.

Agricultural BMPs

<u>Animal waste management systems (AWMS)</u>: AWMS are a significant contributor to simulated WIP reductions, but were absent from the literature review. Experience with the AWMS Expert panel (Hawkins et al. 2016) suggests that this is more a reflection of the state of the literature on that subject, which is limited, than it is about the systematic review or search terms in this case. Even so, enough is known about AWMS and manure storage in particular to conclude that it is less exposed or at risk from expected climate change factors, though in cases where storage or barnyards are directly impacted by precipitation, there is certainly still the opportunity for reduced BMP performance. The AWMS BMP is defined by the CBP in terms of manure "recoverability," and different animal types and variations in farm operations are likely to be more protected against expected climate factors like increased precipitation and runoff. Without additional information from the literature, it is best to avoid speculation and allow more careful consideration of this practice with respect to climate impacts in the future if desired by the CBP partnership given the longevity of manure storage structures and large role of AWMS within the states' WIPs.

Tillage management: Tillage practices, including conservation tillage and no-till, with varying levels of residue coverage, were discussed in a small number of articles, including high quality reviews and meta-analyses such as Blanco-Canqui and Lal (2009) and Ranaivoson et al. (2017). The approach to tillage management may depend on the priority pollutant for a specific location given that occasional tillage (as opposed to no tillage) reduces efficiency with respect to sediment and bound nutrients, but improve efficiency with respect to dissolved nutrients and pesticides (Blanco-Canqui and Wortmann 2020). Perhaps maintaining a minimum level residue to ensure environmental benefits (as recommended by e.g. Blanco-Canqui and Lal (2009)) and utilizing occasional tillage could be combined with vegetative filter strips or other edge-of-field practices to compensate for increased sediment loss while minimizing nutrient leaching. The watershed simulation study by Woznicki et al. (2011) suggests that while conservation tillage may have a smaller effect on pollutant loads than some other agricultural BMPs, its variability in performance is also lower and remains so under future climate conditions.

Cover crops: Though cover crops can be impacted by climate in complex ways (e.g., enhanced by warmer winters or suppressed by fall droughts), they offer the advantage of agility in that each year is an opportunity to plant a different species better adapted to the changing climate, as pointed out by Schmidt et al. (2019). Indeed under some climate scenarios, cover crop performance may be improved. (Bosch et al. 2014a) found that under the moderate B1 climate scenario, cover crop efficiency increased for sediment, N, and P; though efficiency declined slightly under the more extreme A1F1 climate scenario, cover crop mass removal increased for all constituents aside from soluble phosphorus. Schmidt et al. (2019) likewise found that cover crops improved with warming winter climate and were one of the most effective practices for sediment reduction; Schmidt et al. (2019) also found that cover crops were sensitive to temperature changes, but relatively insensitive to precipitation changes.

Nutrient management: Meta-analyses of field studies have emphasized the critical importance of the "4Rs" of nutrient management and returned to the fundamental mass balance to emphasize that the right rate must be in place before the benefits of additional management can be realized (e.g., Chien et al. 2010; Quemada et al. 2013; Xia et al. 2017). Though this point is self-evident, it emphasizes the need for nutrient management to become requisite for agricultural production, regardless of climate impacts.

Urban BMPs

The meta-analysis of Koch et al. (2014) emphasized the importance of "treatment trains", combining multiple BMPs in sequence, since optimal BMP design differs for peak flow attenuation, sediment removal, and nutrient removal. Taking ponds as an example, a larger pond requiring a deeper volume may be warranted to mitigate flooding, but shallow ponds with high surface area to volume ratios are more efficient for nutrient removal (Koch et al. 2014). Extending this example to a future climate scenario (and/or land use change increasing impervious surface area in urban areas), the approach of addressing flow and sediment with one BMP approach in conjunction with another for nutrient removal is likely to become increasingly necessary, though the "treatment train" strategy is not new. What might be considered treatment redundancy under current climate conditions may be warranted under future climate conditions given anticipated reduced BMP efficiency and the conclusion that "it is unrealistic to assume that performance of a specific SW BP will ever be known with a high level of certainty given the large number of variables that could influence performance, knowledge of relative differences in uncertainty should be used to manage risk" (Koch et al. 2014). In considering BMP performance uncertainty and the risk of underperformance, the possibility not only of underperformance but also of pollutant export should also be considered (Hager et al. 2019). In an extensive review of stormwater BMPs, Hager et al. (2019) documented the potential for nutrient export from bioswales, bioretention cells, buffer strips, and green roofs, but not in permeable pavement systems, infiltration trenches, or constructed stormwater wetlands; the occurrence of sediment export from bioswales and bioretention cells was also noted by several of the reviewed studies. Each of these extensive urban BMP reviews highlight the large uncertainties about the variability in stormwater BMP performance and the uncertainty in performance over time, even under stationary climate conditions.

BMP Resilience

Given current understanding of most BMPs' functions and existing state of empirical literature, it is prudent to address BMP resilience in conceptual terms. Conceptually it may help to emulate or follow examples for resilience in other contexts. For instance, (Pelletier et al. 2020) identify factors that decrease or increase resilience for aquatic ecosystems. Some factors such as connectivity, functional redundancy or response diversity, and diversity in management and institutions are likely applicable regarding BMPs as well. Indeed, translating some of the factors discussed by Pelletier et al. (2020) into applicable concepts for BMPs will resemble the kind of design and management principles identified in Wood (2021). Table 16 compares the factors identified in Pelletier et al. (2020) with the principles and adaptations from Wood (2021). There are similarities that can be extracted and applied for BMPs in any sector, not just stormwater, and this can act as a basis for cross- or intra-sector discussions to refine research needs and priorities and identify actions with greater specificity. For example, both articles highlight the importance of redundancies as a way to bolster resilience. Furthermore, the concepts of stressor loads, multiple stressors, connectivity, diversity and heterogeneity from Pelletier et al. (2020) is mirrored by Wood (2021) by promoting the principles of comprehensive watershed management and flow-plains. Both authors are acknowledging how vital it is for a system to have robust, diverse components that are not simply redundant, but evolved or strategically selected in order to complement and enhance each other. In other words, resilience would mean BMPs are designed and implemented in terms of systems or complexes of BMPs as opposed to an a la carte choice that selects one BMP based narrowly on a single criterion such as cost-effectiveness for a target pollutant.

Table 16. Comparison of factors affecting aquatic systems resilience with principles and design adaptations to improve stormwater BMP resilience

<table>
<tr><td>Summarized from Table 2 in Pelletier et al. (2020). See original source for details and references.</td><td>Resilient stormwater design principles, from Wood (2021)</td></tr>
<tr><td>Factors affecting resilience of aquatic systems</td><td rowspan="3">Comprehensive watershed management
Sizing
“Flow-plains”
Full-cycle implementation
Redundancies
Performance enhancers</td></tr>
<tr><td>Direction of Influence: Decreasing</td></tr>
<tr><td>Increasing stressor loads (nutrients and contaminants)
Urbanization
Overharvesting
Climatic changes
Multiple stressors
Lack of equity (in socio-ecological system)</td></tr>
<tr><td>Direction of influence: increasing</td><td>Stormwater BMP design adaptations, from Wood (2021)</td></tr>
<tr><td>Connectivity
Habitat heterogeneity
Functional redundancy
Diversity
Strong linkages between social and ecological systems</td><td rowspan="3">Sizing (e.g., projected IDF curves, use “factor of safety,” over-sizing)
Resilient design adaptations (e.g., “smart” BMPs, media/vegetation amendments, treatment trains, inlet/outlet protections, better maintenance)</td></tr>
<tr><td>Direction of influence: Depends on context</td></tr>
<tr><td>Disturbance
Life history characteristics
Scalar issues</td></tr>
</table>

Range and Variability of BMPs Under Historical Conditions

Some BMPs’ performance can already range from a nutrient or sediment sink to source (for example, Hager et al. (2019); Valenca et al. (2021), among others), with the existing evidence and data associated with historic climate and site conditions. The CBP’s performance estimates for BMPs are based on averages or central tendencies and can misrepresent the possible impact of BMPs when individuals do not understand the context and uncertainties associated with those performance estimates.

We are unable to estimate the relative shift in uncertainties of BMP performance from historic to future climate conditions, largely because we do not fully understand the current range of performance under historic conditions. Lintern et al. (2020) also concludes that not enough is known about BMP functions and performance. Without a finer understanding of individual or groups of BMPs, it is difficult to make educated inferences about the likely shift in BMPs' performance uncertainty or variability. Given the variable status of empirical data to inform our understanding across a wide range of BMPs, it may be possible or prudent to conduct a structured expert elicitation or similar analysis that could generate usable estimates of BMPs' performance probability functions under baseline and future conditions. Such an effort would require a large-scale survey of national or possibly international experts to generate information that could be used by CBP modelers. The process described by Hemming et al. (2018) is one approach, but the CBP modeling team and stakeholders from various partnership groups would need to articulate the desired outcomes and project in much greater detail, potentially as part of a future GIT funding request or STAC workshop depending on the desired structure and outcomes. Information from this report could be adapted for handout materials for prospective respondents, as outlined in (Hemming et al. 2018).

Available evidence (modeling studies) suggest that BMPs will continue to reduce pollutant loads, on average. However, the complete loss of BMP function would be a difficult conclusion for modeling studies to reach. Indeed, complete failure or loss of BMP function is not a conclusion reached by any modeling studies that assess BMP performance, though BMP failure is acknowledged or documented in at least a small percentage of field studies (Lintern et al. 2020). Our review found studies confirming that BMPs can exhibit negative removal of nutrients or sediment (i.e., they increase loads), and from a water quality perspective that could also be considered a failure of the practice. Therefore, we conclude that while BMPs can be expected to continue providing water quality benefits under a future climate, it will remain essential to continually assess and improve our collective understanding of BMPs through multiple lines of evidence (field studies, modeling studies, mixed studies, trends analyses, expert elicitations, and larger syntheses or reviews).

Given the projected increases in nitrogen, phosphorus and sediment yields, the overall performance of most BMPs is expected to decrease in terms of relative reductions (% reductions from increased baseline loads). However, the BMPs may reduce greater loads in absolute terms (pounds) given the greater opportunity represented by increases in runoff, streamflow and load inputs. Nonetheless, overcoming pollutant load increases to meet water quality targets in specific subwatersheds may be challenging at BMP implementation levels acceptable to stakeholders (Bosch et al. 2014a) or require high efficiency treatment of all agricultural and urban land (Renkenberger et al. 2017).

Generally, watershed simulation studies generally indicated that sediment loads were likely to experience largest relative increase under future climate conditions within the Chesapeake Bay watershed (Renkenberger et al. 2017; Wagena and Easton, 2018) and elsewhere in North

America (e.g., Jayakody et al. 2013; Van Liew et al. 2021; Woznicki et al. 2011). However, in the Chesapeake Bay N appears to be the constituent with the greatest risk for nonattainment of TMDL water quality goals (Fischbach et al. 2015; Renkenberger et al. 2017).

We did not find evidence that any specific BMP will cease to offer water quality benefits. This is mostly a reflection of the current status of collective knowledge about BMPs' functions and processes. It is still possible (likelihood unclear), that some versions of particular BMPs are at greater risk to lose or reverse their expected water quality benefits unless updates to their design or management are made. Given existing knowledge gaps, we attempted to identify mechanisms and processes to bridge the gap between climate factors or impacts, with the performance of BMPs. We attempted to identify practices that may be associated with greater risk, given what we can reasonably conclude about the future climate. Individuals or groups of BMPs may be more directly influenced by particular mechanisms, or outside stressors. We tried to focus on stressors that are associated with a changing climate, though it should be emphasized that other stressors and factors can play outsized roles in BMP performance (watershed/regional site characteristics, design, knowledge, skill of installation, maintenance, etc.).

Knowledge Gaps and Future Research Needs

Question 1

1. Better and more accurate climate forecasting and scenarios at spatial and temporal scales needed to inform decision making. Climate forecasting (short term) and scenarios (long term) should be developed to assist decision makers in integrating the most appropriate and relevant information into BMP design, selection, siting, and maintenance.
    a. Evaluate the ability of GCMs or regional climate models to simulate extreme precipitation events.
    b. More studies on the impact of soil moisture on local climates.
2. More research and modeling studies on how climate change impacts runoff processes. Since many BMPs function by reducing runoff volume (e.g., many stormwater BMPs) or by treating runoff (e.g., many agricultural BMPs), more knowledge of how climate change alters runoff volumes, processes, and fractionation (baseflow vs runoff) will be critical to understanding BMP performance.
3. A better understanding of how climate change influences landscape management particularly for agricultural production is critical. Changes to agricultural production due to climate are already occurring. The National Climate Assessments (Gowda et al. 2018) found that increased frequency of droughts, extreme precipitation, and extreme temperatures will continue to have negative effects on production systems. This however, must be reconciled with studies that have found beneficial effects of increased CO_2 concentrations on plant growth (Deryng et al. 2016; Lee et al. 2017).
    a. Evaluate the effects of higher temperatures and CO_2 concentrations, and altered precipitation patterns on agricultural productivity such as nutrient uptake, changes in yield, and altered AET patterns.
    b. Assess how shifts in climate alter agricultural inputs, or intensification.

c. Understand the impacts of changing moisture and temperatures on nutrient cycling.
d. Better understanding of how the CO_2 fertilization effect impacts ET and propagates to influence soil moisture , streamflow, and nutrient cycling.

Question 2
To discuss knowledge gaps and future research needs regarding the impact of climate change on BMP performance, it helps to build from the concepts explained by Lintern et al. (2020), particularly their definitions of *known knowns* ("well-studied aspects"), *known unknowns* ("aspects we know exist but require new knowledge to fully understand"), and *unknown unknowns* ("aspects which we are at this point unable to conceptualize or predict").

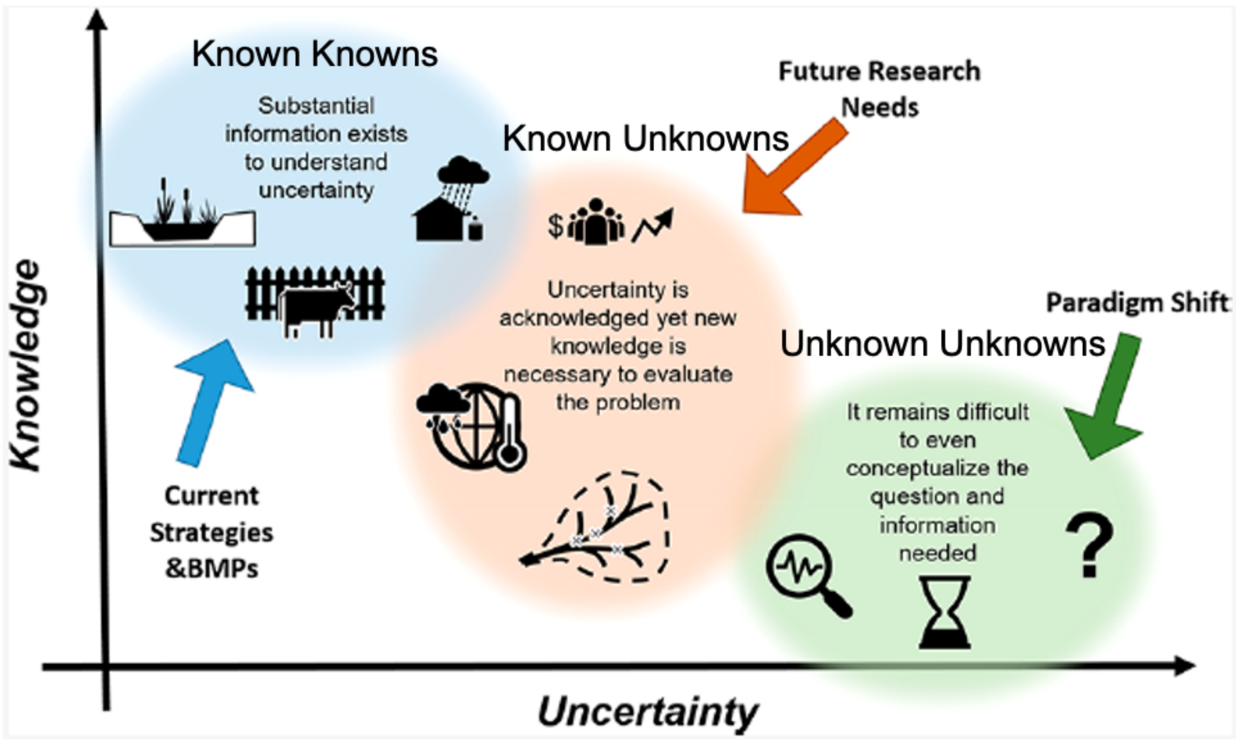


Figure 28. Relationships between current knowledge and strategies, existing future research needs, and future novel directions. Adapted from Lintern et al. (2020).

Much of this report has attempted to understand and describe the uncertainty surrounding current strategies and BMPs (i.e., uncertainty that still remains for *known knowns*), while acknowledging where current information falls short (i.e., the *known unknowns*). The needs for future research described here complement and reinforce those made by (Lintern et al. 2020) and other authors, but these are only one part of an overall adaptive management approach that can strengthen the CBP partnership's ability to identify and address *unknown unknowns* in the future.

Examples of known unknowns identified by this project.

1. Research is needed to help inform the selection, design and siting of cost-effective BMPs that are resilient to anticipated long-term changes in hydroclimatic conditions (Bosch et al. 2018; Williams et al. 2017; Xu et al. 2019). Specifically, there is a need for:
    a. design guidance to increase BMP resilience (e.g., standards for considering the impacts associated with extreme weather and climate into BMP siting and design);
    b. improved simulation modeling capabilities for BMPs;
    c. targeted research to quantify the impacts of climate change on BMP effectiveness, and;
    d. improved methods to evaluate siting and design considerations within the watershed context, in addition to site-level assessment needs (e.g., including BMP cost-effectiveness and co-benefits, Johnson et al. 2018).
2. Need for additional studies that evaluate the influence of climate factors on BMP performance such as Qiu et al. (2020).
3. Modeling studies that assess the performance of one or more BMPs under future climate conditions do not consider alternative land use or growth scenarios beyond changes directly due to the BMPs. This is an understandable knowledge gap given the purpose of the reviewed modeling studies is to understand the effectiveness of one or more BMPs in isolation of other changes. However, population growth and other socioeconomic factors will drive significant changes to the landscape and it is well established that that landscape will be a major factor in watershed loads. While the uncertainty of future growth projections may be quite high towards the long term, it may be worthwhile for researchers to consider how they might utilize short-or medium-term growth projections in coordination with BMP modeling to assess impacts to loads and BMP effectiveness.
4. It is almost certain that the systematic review approach did not identify all critically relevant or significant studies, especially when the literature searches were done for such a wide range of conservation practices. A similar systematic review approach may be appropriate for specific practices or classes of practices in the future. However, if a future effort is made across a similarly broad scope of sectors or practices, it may be better to use a focused review approach that builds from references to, and works cited by, key papers.
5. Social science linkages were not sought in our searches and review, but there are significant potential contributions of social science fields particularly with respect to improved implementation, installation or maintenance of BMPs. Our scope did not include considerations of socioeconomic factors or research. In light of climate change's disparate impact on underserved populations, future efforts that include social science research should also include social and environmental justice within the lens to understand the benefits or potential impacts of large scale BMP implementation for more than water quality benefits alone.

As noted earlier, our ability to recognize existing knowledge gaps is limited to improvements of understanding of existing uncertainties for known knowns, as well as acknowledged shortcomings in current knowledge (*known unknowns*). However, as the climate continues to change alongside land development and BMP implementation, it is expected that new *unknown unknowns* will emerge, and that while these concepts are undefinable and unpredictable by their very nature, it is still possible to prepare for their occurrence. (Lintern et al. 2020) suggest three approaches: use of machine learning, applying methods from business and operations management, and leveraging long term convergent research. The first two certainly have merits but are outside the scope of our efforts here and should be considered by regional groups of experts with the relevant knowledge. Here, it is worth elaborating on the convergent research recommendation from Lintern and colleagues, who describe challenges to such convergent research, which will ring true for those familiar with complex watershed management partnerships such as the Chesapeake Bay Program:

- Inconsistent cross-disciplinary language and terminology
- Struggles to engage with key stakeholders
- Barriers to establish methods that are reproducible and understandable
- Time-lag between management decisions and environmental outcomes or milestones

They allude to some of the ways in which these challenges can be overcome, such as networking of scholars and practitioners, development opportunities, increased engagement with practitioners and decision makers throughout research activities, etc. They also point to the lack of funding mechanisms, especially when it comes to larger and longer-term funding that is often required for effective convergent research to tackle a transdisciplinary problem like nutrient pollution.

These challenges are ripe for groups within the Chesapeake Bay Program structure to address, and in many ways the CBP partnership already facilitates this type of longer-term thinking to encourage convergent research. The roles of groups like the Scientific and Technical Advisory Committee (STAC) and the Scientific, Technical Assessment and Reporting (STAR) team in particular can be leveraged toward sustaining long-term convergent research that may identify unknown unknowns, either for climate change, BMPs, or for entirely new but equally vital environmental concerns. They may also be able to lay a foundation for convergent research by guiding and encouraging the CBP to establish consistent cross-disciplinary terminology. Valuable resources to inform this effort with respect to BMPs would come from BMP databases such as the International Stormwater BMP Database and more recently developed companion Agricultural BMP Database, newly released Stream Restoration Database, and also the Measured Annual Nutrient loads from AGricultural Environments (MANAGE) database. Such databases have been one approach toward consistent terminology and methodology and at a minimum encourage reporting meta-data for the methodologies. However, the completeness of reported application/environmental and research method variables (design, management, site, etc. are a big limitation as pointed out by Koch et al. (2014) in their evaluation of the urban stormwater BMP database. In their analysis of the MANAGE database, Nummer et al. (2018) noted the non-random application of BMPs within land use for agricultural applications, raising an important consideration for statistical assessment of such data.

Due to this review's focus on BMPs for water quality we do not consider a number of closely related systems or practices. For instance, stormwater BMPs discussed in this report work in conjunction with combined or separate storm sewer systems in developed areas. This report has attempted to draw conclusions from the literature about how climate may impact the variability or uncertainty around BMPs, but future work across sectors or within the developed sector may want to directly consider the interrelated effects between BMPs and established infrastructure (gray infrastructure). Aging infrastructure may be a large focus of state and federal partners, especially over the next decade in light of recent federal legislation. There will be a need to consider expected shifts from climate change when designing and installing gray infrastructure the same way that such updated information is needed to inform design and implementation of nonpoint source BMPs. Effort should be made to ensure that knowledge and assumptions that develop and are applied within gray infrastructure circles (water, wastewater, stormwater, roads, etc.) are shared with planners and technical assistance providers in the nonpoint source sector.

Recommendations for the CBP

Develop mechanisms for publication of aggregated BMP inspection failure data. The CBP should consolidate and publish available inspection data collected and reported by the jurisdictions. As noted in this synthesis and others such as Lintern et al. (2020), the BMP performance literature rarely, if ever, includes instances of BMP failures. This has proven to be problematic for BMP expert panels when published data about BMP failure rates is so scarce. Basic data about inspection failure rates would be a first step, and long term the inspection data - at least for priority BMPs - could perhaps include simple information regarding the cause or extent of the failure. Currently this data is absent in the published literature, and the foundation offered by CBP partnership's BMP verification framework would enable the jurisdictions and the CBP to fill a significant gap in the knowledge base about BMP longevity.

Encourage and incentivize partnerships between researchers and jurisdictions' BMP verification programs to collect and publish more long-term BMP performance data. When the CBP adopted its BMP Verification Framework it included a note about a future desire to leverage data collection opportunities through verification site-visits or inspections, or other methods, to also gather BMP performance data (page 49-50 of framework document). This stemmed from suggestions by the BMP Verification Review Panel and STAC, and STAC was tasked to develop and implement such a data collection and analysis program with the CBP and jurisdictions. No such effort materialized, likely due to a lack of resources and capacity, in addition to a large number of competing science needs and priorities. The CBP or STAC may not have the capacity themselves to operate such a program, but through its grants the CBP may have opportunities to more directly encourage researchers and experts to partner with jurisdictional agencies to confidentially collect and assess BMP performance data for subsequent publication. To the extent that BMP performance data is already encouraged or collected through funding mechanisms or partnerships, such as Chesapeake Bay Watershed grants by the National Fish and Wildlife Foundation (NFWF), the CBP should ensure that any BMP performance data is periodically published in a searchable database or publicly accessible report that can be used by interested researchers, and would include data fields as suggested by Liu et al. (2017).

More mechanistic BMP modeling studies. Develop more mechanistic modeling of individual (or suites of BMPs) under baseline and altered climatic conditions. Current CBP modeling efforts are better suited to represent how climate change might influence nonpoint source pollution loads reaching BMPs by representing a change in generation, transport, and–to some extent–storage within the landscape. The influence of predicted changes in land use and management decisions in both agricultural and urban settings on N, P, and sediment loading is an area of active research also captured in simulation models. The model evaluations of climate impacts on BMP efficiency discussed in this report largely reflected changes in pollutant loads. Some BMPs, like vegetative filter strips in SWAT, are represented more mechanistically, as the governing relationships are developed and supported by extensive literature and, importantly, relatively simple to conceptualize. Other BMPs are modeled mechanistically but with less certainty that all of the relevant processes are adequately represented (e.g., cover crops). Yet many BMPs are essentially modeled as static reduction efficiencies.

While the lack of sufficient information to model the effect of climate change on BMP performance has been acknowledged in the CBP climate change analysis process, additional data or analysis may not substantially decrease BMP performance uncertainty. With a multitude of factors affecting BMP performance, disentangling the potential impact of climate change is difficult. Refocusing on characterizing relative BMP uncertainty from empirical evidence is likely more useful than reducing uncertainty in central tendency for supporting evaluation of climate effects.

Leverage existing adaptive management efforts to establish a CBP agenda for research and science needs related to BMPs and climate change, with priority on communication of “no-lose” directions. There are long-standing and ongoing efforts within the CBP to better articulate and understand the state of knowledge and research needs pertaining to BMPs in a changing climate. This report grew from such discussions and the concepts, findings and recommendations documented here will augment the CBP’s efforts moving forward. The details and direction of the research agenda are the prerogative of the CBP partnership, not the authors of this study, but it is recommended that the CBP utilize its network of experts and communication professionals to identify and communicate strategies that have zero or minimal chance of negative impacts. For example, the protection and conservation of existing high-functioning natural areas will remain an effective strategy for water quality and numerous other environmental outcomes regardless of future climate conditions.

Develop mechanisms of quantifying BMP efficiency uncertainty under climate change. The evolution of the watershed model makes analysis of multiple potential outcomes relatively straightforward. In this context, it becomes possible to consider the implications of BMP performance uncertainty by simply assuming and simulating alternative efficiencies. At its most basic, this could simply be changing the efficiencies, over some range of BMP performance, especially if the shape of BMP performance distributions are unknown (but the range of BMP efficiencies are known). More complex would be to probabilistically simulate BMP performance, informed by information not only about the range and central tendency of BMP performance, but also about the shape of the BMP efficiency distribution.

Expert elicitation to determine alterations to BMP Efficiencies. The CBP partnership has an urgent need to account for the impact that climate change may have on BMPs' effectiveness, but the uncertainty in performance extends to management and other complex non-climate factors which are poorly understood in the literature for most BMPs. Without accounting for climate impacts and performance uncertainty the CBP may not be setting realistic expectations of BMP implementation necessary to achieve water quality goals. However, the information needed to simulate these factors is not available in the literature, as seen through this synthesis. The CBP can still gather the necessary information.

The most cost-effective, robust and timely option would be a comprehensive expert elicitation project that would encompass all existing BMPs. The elicitation could build from this synthesis report, drawing heavily from this document to serve as background materials that are needed in two-step processes such as those described in Farr et al. (2021) and Hemming et al. (2018), which are functionally similar in their approach. Both examples also provide samples and templates in terms of background and explanatory materials to provide for participating experts. As an additional example, the most recent wetland expert panel (Law et al. 2020) used the elicitation framework from Hemming et al. (2018) to garner relative effectiveness estimates and while accounting for experts' relative confidence or certainty.

This expert elicitation project would likely fit within the budget and constraints of a GIT-funding project, and possibly even a Scientific and Technical Advisory Committee (STAC) workshop if the workshop is split into two stages. The former may be best suited to the task as it would ideally draw proposals from parties with prior experience in such projects and who would conduct the contracted tasks, while the latter would depend heavily on volunteer efforts of the workshop steering committee. Perhaps other funding options would be available, if these standing annual options do not work.

Regardless of the funding method, the elicitation could be carried out and completed well in advance of 2026, when it is expected that the CBP modeling team would be ready to incorporate estimated adjustments to BMP effectiveness due to climate change.

References

Abalos, D., S. Jeffery, A. Sanz-Cobena, G. Guardia, and A. Vallejo. 2014. "Meta-Analysis of the Effect of Urease and Nitrification Inhibitors on Crop Productivity and Nitrogen Use Efficiency." *Agriculture, Ecosystems & Environment* 189:136–44. doi: 10.1016/j.agee.2014.03.036.

Alam, M. J., J. L. Goodall, B. D. Bowes, and E. H. Girvetz. 2017. "The Impact of Projected Climate Change Scenarios on Nitrogen Yield at a Regional Scale for the Contiguous United States." *JAWRA Journal of the American Water Resources Association* 53(4):854–70. doi: 10.1111/1752-1688.12537.

Alizad, K., S. C. Hagen, S. C. Medeiros, M. V. Bilskie, J. T. Morris, L. Balthis, and C. A. Buckel. 2018. "Dynamic Responses and Implications to Coastal Wetlands and the Surrounding Regions under Sea Level Rise." *Plos One* 13(10). doi: 10.1371/journal.pone.0205176.

Ardon, M., J. L. Morse, B. P. Colman, and E. S. Bernhardt. 2013. "Drought-Induced Saltwater Incursion Leads to Increased Wetland Nitrogen Export." *Global Change Biology* 19(10):2976–85. doi: 10.1111/gcb.12287.

Ator, S. W., J. D. Blomquist, J. S. Webber, and J. G. Chanat. 2020. "Factors Driving Nutrient Trends in Streams of the Chesapeake Bay Watershed." *Journal of Environmental Quality* 49(4):812–34. doi: 10.1002/jeq2.20101.

Ator, S. W., A. M. García, G. E. Schwarz, J. D. Blomquist, and A. J. Sekellick. 2019. "Toward Explaining Nitrogen and Phosphorus Trends in Chesapeake Bay Tributaries, 1992–2012." *JAWRA Journal of the American Water Resources Association* 55(5):1149–68. doi: 10.1111/1752-1688.12756.

Bader, D., C. Covey, W. Gutowski, I. Held, K. Kunkel, R. Miller, R. Tokmakian, and M. Zhang. 2008. "Climate Models: An Assessment of Strengths and Limitations." *Geological and Atmospheric Sciences Reports*.

Ballantine, K., and R. Schneider. 2009. "Fifty-Five Years of Soil Development in Restored Freshwater Depressional Wetlands." *Ecological Applications* 19(6):1467–80. doi: 10.1890/07-0588.1.

Ballard, T. C., E. Sinha, and A. M. Michalak. 2019. "Long-Term Changes in Precipitation and Temperature Have Already Impacted Nitrogen Loading." *Environmental Science & Technology* 53(9):5080–90. doi: 10.1021/acs.est.8b06898.

Bergtold, J. S., S. Ramsey, L. Maddy, and J. R. Williams. 2017. "A Review of Economic Considerations for Cover Crops as a Conservation Practice." *Renewable Agriculture and Food Systems* 34(1):62–76. doi: 10.1017/s1742170517000278.

Bernhard, A. E., C. Dwyer, A. Idrizi, G. Bender, and R. Zwick. 2015. "Long-Term Impacts of Disturbance on Nitrogen-Cycling Bacteria in a New England Salt Marsh." *Frontiers in Microbiology* 6. doi: 10.3389/fmicb.2015.00046.

Bhatt, R., and A. Hossain. 2019. "Concept and Consequence of Evapotranspiration for Sustainable Crop Production in the Era of Climate Change." *Adv. Evapotranspiration Methods Appl* 1:1–13.

Blanco-Canqui, H., and R. Lal. 2009. “Crop Residue Removal Impacts on Soil Productivity and Environmental Quality.” *Critical Reviews in Plant Sciences* 28(3):139–63. doi: 10.1080/07352680902776507.

Blanco-Canqui, H., and C. S. Wortmann. 2020. “Does Occasional Tillage Undo the Ecosystem Services Gained with No-till? A Review.” *Soil and Tillage Research* 198. doi: 10.1016/j.still.2019.104534.

Boesch, D., L. Atkinson, W. Boicourt, J. Boon, D. Cahoon, R. Dalrymple, T. Ezer, B. Horton, Z. Johnson, R. Kopp, M. Li, R. Moss, A. Parris, and C. Sommerfield. 2013. “Updating Maryland’s Sea-Level Rise Projections.” *CCPO Publications*.

Boger, A. R., L. Ahiablame, E. Mosase, and D. Beck. 2018. “Effectiveness of Roadside Vegetated Filter Strips and Swales at Treating Roadway Runoff: A Tutorial Review.” *Environmental Science: Water Research & Technology* 4(4):478–86. doi: 10.1039/c7ew00230k.

Bosch, D. J., M. B. Wagena, A. C. Ross, A. S. Collick, and Z. M. Easton. 2018. “Meeting Water Quality Goals under Climate Change in Chesapeake Bay Watershed, USA.” *JAWRA Journal of the American Water Resources Association* 54(6):1239–57. doi: 10.1111/1752-1688.12684.

Bosch, N. S., M. A. Evans, D. Scavia, and J. D. Allan. 2014a. “Interacting Effects of Climate Change and Agricultural BMPs on Nutrient Runoff Entering Lake Erie.” *Journal of Great Lakes Research* 40(3):581–89.

Bosch, N. S., M. A. Evans, D. Scavia, and J. D. Allan. 2014b. “Interacting Effects of Climate Change and Agricultural BMPs on Nutrient Runoff Entering Lake Erie.” *Journal of Great Lakes Research* 40(3):581–89. doi: 10.1016/j.jglr.2014.04.011.

Brantley, C. G., J. W. Day Jr., R. R. Lane, E. Hyfield, J. N. Day, and J.-Y. Ko. 2008. “Primary Production, Nutrient Dynamics, and Accretion of a Coastal Freshwater Forested Wetland Assimilation System in Louisiana.” *Ecological Engineering* 34(1):7–22. doi: 10.1016/j.ecoleng.2008.05.004.

Brisson, J., M. Rodriguez, C. A. Martin, and R. Proulx. 2020. “Plant Diversity Effect on Water Quality in Wetlands: A Meta-Analysis Based on Experimental Systems.” *Ecological Applications* 30(4). doi: 10.1002/eap.2074.

Buffington, K. J., C. N. Janousek, K. M. Thorne, and B. D. Dugger. 2020. “Spatiotemporal Patterns of Mineral and Organic Matter Deposition Across Two San Francisco Bay-Delta Tidal Marshes.” *Wetlands* 40(5):1395–1407. doi: 10.1007/s13157-019-01259-3.

Burgin, A. J., and S. K. Hamilton. 2007. “Have We Overemphasized the Role of Denitrification in Aquatic Ecosystems? A Review of Nitrate Removal Pathways.” *Frontiers in Ecology and the Environment* 5(2):89–96. doi: 10.1890/1540-9295(2007)5[89:HWOTRO]2.0.CO;2.

Butterbach-Bahl, K., and M. Dannenmann. 2011. “Denitrification and Associated Soil N2O Emissions Due to Agricultural Activities in a Changing Climate.” *Carbon and Nitrogen Cycles* 3(5):389–95. doi: 10.1016/j.cosust.2011.08.004.

Caffrey, J. M., J. T. Hollibaugh, and B. Mortazavi. 2016. “Living Oysters and Their Shells as Sites of Nitrification and Denitrification.” *Marine Pollution Bulletin* 112(1–2):86–90. doi: 10.1016/j.marpolbul.2016.08.038.

Callaway, J. C., V. T. Parker, M. C. Vasey, and L. M. Schile. 2007. “Emerging Issues for the Restoration of Tidal Marsh Ecosystems in the Context of Predicted Climate Change.” *Madrono* 54(3):234–48. doi: 10.3120/0024-9637(2007)54[234:eiftro]2.0.co;2.

Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. “Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen.” *Ecological Applications* 8(3):559–68. doi: 10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2.

Cecchetti, A. R., A. N. Stiegler, K. E. Graham, and D. L. Sedlak. 2020. “The Horizontal Levee: A Multi -Benefit Nature-Based Treatment System That Improves Water Quality and Protects Coastal Levees from the Effects of Sea Level Rise.” *Water Research X* 7. doi: 10.1016/j.wroa.2020.100052.

Cerco, C. F. 2016. “Conowingo Reservoir Sedimentation and Chesapeake Bay: State of the Science.” *Journal of Environmental Quality* 45(3):882–86. doi: 10.2134/jeq2015.05.0230.

Chanat, J. G., and G. Yang. 2018. “Exploring Drivers of Regional Water-Quality Change Using Differential Spatially Referenced Regression—A Pilot Study in the Chesapeake Bay Watershed.” *Water Resources Research* 54(10):8120–45. doi: 10.1029/2017WR022403.

Chang, H., B. M. Evans, and D. R. Easterling. 2001. “The Effects of Climate Change on Stream Flow and Nutrient Loading1.” *JAWRA Journal of the American Water Resources Association* 37(4):973–85. doi: 10.1111/j.1752-1688.2001.tb05526.x.

Chesapeake Bay Program. 2015. “Protocol for the Development, Review, and Approval of Loading and Effectiveness Estimates for Nutrient and Sediment Controls in the Chesapeake Bay Watershed Model.” Retrieved (https://www.chesapeakebay.net/documents/CBP_BMP_Expert_Panel_Protocol_WQGIT_approved_7.13.15.pdf).

Chesapeake Bay Program. 2020. “Chesapeake Assessment and Scenario Tool (CAST) Version 2019.” *Chesapeake Bay Program Office*. Retrieved November 1, 2021 (https://cast.chesapeakebay.net/about).

Chiang, L.-C., I. Chaubey, N.-M. Hong, Y.-P. Lin, and T. Huang. 2012. “Implementation of BMP Strategies for Adaptation to Climate Change and Land Use Change in a Pasture-Dominated Watershed.” *International Journal of Environmental Research and Public Health* 9(10):3654–84. doi: 10.3390/ijerph9103654.

Chichakly, K. J., W. B. Bowden, and M. J. Eppstein. 2013. “Minimization of Cost, Sediment Load, and Sensitivity to Climate Change in a Watershed Management Application.” *Environmental Modelling & Software* 50:158–68. doi: 10.1016/j.envsoft.2013.09.009.

Chien, S. H., L. I. Prochnow, S. Tu, and C. S. Snyder. 2010. “Agronomic and Environmental Aspects of Phosphate Fertilizers Varying in Source and Solubility: An Update Review.” *Nutrient Cycling in Agroecosystems* 89(2):229–55. doi: 10.1007/s10705-010-9390-4.

Cousino, L. K., R. H. Becker, and K. A. Zmijewski. 2015. “Modeling the Effects of Climate Change on Water, Sediment, and Nutrient Yields from the Maumee River Watershed.” *Journal of Hydrology: Regional Studies* 4:762–75. doi: 10.1016/j.ejrh.2015.06.017.

Cristan, R., W. M. Aust, M. C. Bolding, S. M. Barrett, J. F. Munsell, and E. Schilling. 2016. “Effectiveness of Forestry Best Management Practices in the United States: Literature Review.” *Forest Ecology and Management* 360:133–51. doi: 10.1016/j.foreco.2015.10.025.

Davidson, E. A., and I. A. Janssens. 2006. “Temperature Sensitivity of Soil Carbon Decomposition and Feedbacks to Climate Change.” *Nature* 440(7081):165–73. doi: https://doi.org/10.1038/nature04514.

DePhilip, M., and T. Moberg. 2010. “Ecosystem Flow Recommendations for the Susquehanna River Basin.” *The Nature Conservancy: Harrisburg, PA, USA*.

Deryng, D., J. Elliott, C. Folberth, C. Müller, T. A. M. Pugh, K. J. Boote, D. Conway, A. C. Ruane, D. Gerten, J. W. Jones, N. Khabarov, S. Olin, S. Schaphoff, E. Schmid, H. Yang, and C. Rosenzweig. 2016. “Regional Disparities in the Beneficial Effects of Rising CO2 Concentrations on Crop Water Productivity.” *Nature Climate Change* 6(8):786–90. doi: 10.1038/nclimate2995.

Donner, S., B. Frost, and M. H. Goulet. 2016. *Recommendations of the Expert Panel to Define Removal Rates for Street and Storm Drain Cleaning Practices. Final Report.*

Doroski, A. A., A. M. Helton, and T. M. Vadas. 2019. “Denitrification Potential and Carbon Mineralization in Restored and Unrestored Coastal Wetland Soils Across an Urban Landscape.” *Wetlands* 39(4):895–906. doi: 10.1007/s13157-019-01128-z.

Easterling, D. R., J. R. Arnold, T. Knutson, K. E. Kunkel, A. N. LeGrande, L. R. Leung, R. S. Vose, D. E. Waliser, and M. F. Wehner. 2017. *Precipitation Change in the United States. Climate Science Special Report: Fourth National Climate Assessment, Volume I*. U.S. Global Change Research Program. doi: 10.7930/J0H993CC.

Elliott, J., D. Deryng, C. Müller, K. Frieler, M. Konzmann, D. Gerten, M. Glotter, M. Flörke, Y. Wada, N. Best, S. Eisner, B. M. Fekete, C. Folberth, I. Foster, S. N. Gosling, I. Haddeland, N. Khabarov, F. Ludwig, Y. Masaki, S. Olin, C. Rosenzweig, A. C. Ruane, Y. Satoh, E. Schmid, T. Stacke, Q. Tang, and D. Wisser. 2014. “Constraints and Potentials of Future Irrigation Water Availability on Agricultural Production under Climate Change.” *Proceedings of the National Academy of Sciences* 111(9):3239–44. doi: 10.1073/pnas.1222474110.

Farr, E. R., M. R. Johnson, M. W. Nelson, J. A. Hare, W. E. Morrison, M. D. Lettrich, B. Vogt, C. Meaney, U. A. Howson, P. J. Auster, F. A. Borsuk, D. C. Brady, M. J. Cashman, P. Colarusso, J. H. Grabowski, J. P. Hawkes, R. Mercaldo-Allen, D. B. Packer, and D. K. Stevenson. 2021. “An Assessment of Marine, Estuarine, and Riverine Habitat Vulnerability to Climate Change in the Northeast U.S.” *PLOS ONE* 16(12):e0260654. doi: 10.1371/journal.pone.0260654.

Fischbach, J. R., M. E. Miro, K. Romita Grocholski, A. T. DeGaetano, and S. Borisoff. 2019. *Chesapeake Bay Climate Impacts Summary and Outlook: Winter 2018-2019: Seasonal Precipitation Analysis*. Santa Monica, CA: RAND Corporation.

Fleri, J. R., S. Lera, A. Gerevini, L. Staver, and W. Nardin. 2019. “Empirical Observations and Numerical Modelling of Tides, Channel Morphology, and Vegetative Effects on Accretion in a Restored Tidal Marsh.” *Earth Surface Processes and Landforms* 44(11):2223–35. doi: 10.1002/esp.4646.

Gavric, S., G. Leonhardt, J. Marsalek, and M. Viklander. 2019. “Processes Improving Urban Stormwater Quality in Grass Swales and Filter Strips: A Review of Research Findings.” *Sci Total Environ* 669:431–47. doi: 10.1016/j.scitotenv.2019.03.072.

Gedan, K. B., R. Epanchin-Niell, and M. Qi. 2020. “Rapid Land Cover Change in a Submerging Coastal County.” *Wetlands* 40(6):1717–28. doi: 10.1007/s13157-020-01328-y.

Giese, E., A. Rockler, A. Shirmohammadi, and M. A. Pavao-Zuckerman. 2019. “Assessing Watershed-Scale Stormwater Green Infrastructure Response to Climate Change in Clarksburg, Maryland.” *Journal of Water Resources Planning and Management* 145(10):05019015. doi: 10.1061/(ASCE)WR.1943-5452.0001099.

Giuffria, J. M., D. J. Bosch, D. B. Taylor, and N. Alamdari. 2017. “Costs of Water Quality Goals under Climate Change in Urbanizing Watersheds: Difficult Run, Virginia.” *Journal of Water Resources Planning and Management* 143(9):04017055. doi: 10.1061/(ASCE)WR.1943-5452.0000782.

Gleick, P. H. 1989. “Climate Change, Hydrology, and Water Resources.” *Reviews of Geophysics* 27(3):329–44. doi: 10.1029/RG027i003p00329.

Goh, H. W., K. S. Lem, N. A. Azizan, C. K. Chang, A. Talei, C. S. Leow, and N. A. Zakaria. 2019. “A Review of Bioretention Components and Nutrient Removal under Different Climates-Future Directions for Tropics.” *Environ Sci Pollut Res Int* 26(15):14904–19. doi: 10.1007/s11356-019-05041-0.

Gowda, P. H., J. Steiner, C. Olson, M. Boggess, T. Farrigan, and M. A. Grusak. 2018. *Agriculture and Rural Communities. In Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (Eds.)]*. Washington, DC, USA: U.S. Global Change Research Program. doi: 10.7930/NCA4.2018.CH10.

Groffman, P. M., K. Butterbach-Bahl, R. W. Fulweiler, A. J. Gold, J. L. Morse, E. K. Stander, C. Tague, C. Tonitto, and P. Vidon. 2009a. “Challenges to Incorporating Spatially and Temporally Explicit Phenomena (Hotspots and Hot Moments) in Denitrification Models.” *Biogeochemistry* 93(1):49–77. doi: 10.1007/s10533-008-9277-5.

Groffman, P. M., K. Butterbach-Bahl, R. W. Fulweiler, A. J. Gold, J. L. Morse, E. K. Stander, C. Tague, C. Tonitto, and P. Vidon. 2009b. “Challenges to Incorporating Spatially and Temporally Explicit Phenomena (Hotspots and Hot Moments) in Denitrification Models.” *Biogeochemistry* 93(1/2):49–77. doi: 10.1007/s10533-008-9277-5.

Hager, J., G. Hu, K. Hewage, and R. Sadiq. 2019. “Performance of Low-Impact Development Best Management Practices: A Critical Review.” *Environmental Reviews* 27(1):17–42. doi: 10.1139/er-2018-0048.

Hatfield, J. L., and J. H. Prueger. 2004. “Impacts of Changing Precipitation Patterns on Water Quality.” *Journal of Soil and Water Conservation* 59(1):51–58.

Hawkins, S., D. Hamilton, B. McIntosh, J. Moyle, M. Risse, and P. Vanderstappen. 2016. *Animal Waste Management Systems: Recommendations from the BMP Expert Panel for Animal Waste Management Systems in the Phase 6 Watershed Model. Hawkins, S. and J. Hanson, Editors.* CBP/TRS-315-16. Approved by CBP WQGIT.

Hawkins, T. W. 2015. “Simulating the Impacts of Projected Climate Change on Streamflow Hydrology for the Chesapeake Bay Watershed.” *Annals of the Association of American Geographers* 105(4):627–48. doi: 10.1080/00045608.2015.1039108.

Hayhoe, K., C. P. Wake, T. G. Huntington, L. Luo, M. D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. J. Troy, and D. Wolfe. 2007. “Past and Future Changes in Climate and Hydrological Indicators in the US Northeast.” *Climate Dynamics* 28(4):381–407. doi: 10.1007/s00382-006-0187-8.

Hemming, V., M. A. Burgman, A. M. Hanea, M. F. McBride, and B. C. Wintle. 2018. “A Practical Guide to Structured Expert Elicitation Using the IDEA Protocol.” *Methods in Ecology and Evolution* 9(1):169–80. doi: 10.1111/2041-210X.12857.

Hopkins, K. G., J. V. Loperfido, L. S. Craig, G. B. Noe, and D. M. Hogan. 2017. “Comparison of Sediment and Nutrient Export and Runoff Characteristics from Watersheds with

Centralized versus Distributed Stormwater Management." *Journal of Environmental Management* 203(1):286–98. doi: 10.1016/j.jenvman.2017.07.067.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

Huang, H., J. M. Winter, E. C. Osterberg, R. M. Horton, and B. Beckage. 2017. "Total and Extreme Precipitation Changes over the Northeastern United States." *Journal of Hydrometeorology* 18(6):1783–98. doi: 10.1175/JHM-D-16-0195.1.

Huang, L., G. Zhang, J. Bai, Z. Xia, W. Wang, J. Jia, X. Wang, X. Liu, and B. Cui. 2021. "Desalinization via Freshwater Restoration Highly Improved Microbial Diversity, Co-Occurrence Patterns and Functions in Coastal Wetland Soils." *Science of the Total Environment* 765. doi: 10.1016/j.scitotenv.2020.142769.

Huntington, T. G. 2003. "Climate Warming Could Reduce Runoff Significantly in New England, USA." *Agricultural and Forest Meteorology* 117(3–4):193–201. doi: 10.1016/S0168-1923(03)00063-7.

Jahangir, M. M. R., K. G. Richards, M. G. Healy, L. Gill, C. Müller, P. Johnston, and O. Fenton. 2016. "Carbon and Nitrogen Dynamics and Greenhouse Gas Emissions in Constructed Wetlands Treating Wastewater: A Review." *Hydrology and Earth System Sciences* 20(1):109–23. doi: 10.5194/hess-20-109-2016.

Jayakody, P., P. B. Parajuli, and T. P. Cathcart. 2014. "Impacts of Climate Variability on Water Quality with Best Management Practices in Sub-Tropical Climate of USA: CLIMATE VARIABILITY ON WATER QUALITY WITH BEST MANAGEMENT PRACTICES." *Hydrological Processes* 28(23):5776–90. doi: 10.1002/hyp.10088.

Johnson, W. C., M. D. Dixon, M. L. Scott, L. Rabbe, G. Larson, M. Volke, and B. Werner. 2012. "Forty Years of Vegetation Change on the Missouri River Floodplain." *BioScience* 62(2):123–35. doi: 10.1525/bio.2012.62.2.6.

Johnson, Z., M. Bennett, L. Linker, S. Julius, R. Najjar, M. Mitchell, D. Montali, and R. Dixon. 2016. "The Development of Climate Projections for Use in Chesapeake Bay Program Assessments." *Scientific and Technical Advisory Committee (STAC), Chesapeake Bay Program. STAC Publication* (16–006).

Johnson, Z., S. Julius, J. Fischbach, M. Bennett, B. Benham, D. Sample, and K. Stephenson. 2018. *Monitoring and Assessing Impacts of Changes in Weather Patterns and Extreme Events on BMP Siting and Design*. 18–004. STAC.

Kadlec, R. H., and K. r. Reddy. 2001. "Temperature Effects in Treatment Wetlands." *Water Environment Research* 73(5):543–57. doi: 10.2175/106143001X139614.

Kaushal, S. S., P. M. Groffman, L. E. Band, C. A. Shields, R. P. Morgan, M. A. Palmer, K. T. Belt, C. M. Swan, S. E. Findlay, and G. T. Fisher. 2008. "Interaction between Urbanization and Climate Variability Amplifies Watershed Nitrate Export in Maryland." *Environmental Science & Technology* 42(16):5872–78.

Keisman, J. L., O. H. Devereux, A. E. LaMotte, A. J. Sekellick, and J. D. Blomquist. 2018. *Manure and Fertilizer Inputs to Land in the Chesapeake Bay Watershed, 1950–2012*. Vols.

2018–5022. *USGS Numbered Series*. 2018–5022. Reston, VA: U.S. Geological Survey. doi: 10.3133/sir20185022.

Kimball, B. A., and S. B. Idso. 1983. "Increasing Atmospheric CO2: Effects on Crop Yield, Water Use and Climate." *Plant Production and Management under Drought Conditions* 7(1):55–72. doi: 10.1016/0378-3774(83)90075-6.

Kirwan, M. L., and K. B. Gedan. 2019. "Sea-Level Driven Land Conversion and the Formation of Ghost Forests." *Nature Climate Change* 9(6):450–57. doi: 10.1038/s41558-019-0488-7.

Koch, B. J., C. M. Febria, M. Gevrey, L. A. Wainger, and M. A. Palmer. 2014. "Nitrogen Removal by Stormwater Management Structures: A Data Synthesis." *JAWRA Journal of the American Water Resources Association* 50(6):1594–1607. doi: 10.1111/jawr.12223.

Koelsch, R. 2005. "Evaluating Livestock System Environmental Performance with Whole-Farm Nutrient Balance." *J Environ Qual* 34(1):149–55.

Kominoski, J. S., E. E. Gaiser, E. Castaneda-Moya, S. E. Davis, S. B. Dessu, P. Julian II, D. Y. Lee, L. Marazzi, V. H. Rivera-Monroy, A. Sola, U. Stingl, S. Stumpf, D. Surratt, R. Travieso, and T. G. Troxler. 2020. "Disturbance Legacies Increase and Synchronize Nutrient Concentrations and Bacterial Productivity in Coastal Ecosystems." *Ecology* 101(5). doi: 10.1002/ecy.2988.

Kratky, H., Z. Li, Y. Chen, C. Wang, X. Li, and T. Yu. 2017. "A Critical Literature Review of Bioretention Research for Stormwater Management in Cold Climate and Future Research Recommendations." *Frontiers of Environmental Science & Engineering* 11(4). doi: 10.1007/s11783-017-0982-y.

Kubota, H., M. Iqbal, S. Quideau, M. Dyck, and D. Spaner. 2018. "Agronomic and Physiological Aspects of Nitrogen Use Efficiency in Conventional and Organic Cereal-Based Production Systems." *Renewable Agriculture and Food Systems* 33(5):443–66. doi: 10.1017/S1742170517000163.

Lal, R. 1998. "Soil Erosion Impact on Agronomic Productivity and Environment Quality." *Critical Reviews in Plant Sciences* 17(4):319–464. doi: 10.1080/07352689891304249.

Lammerts van Bueren, E. T., and P. C. Struik. 2017. "Diverse Concepts of Breeding for Nitrogen Use Efficiency. A Review." *Agronomy for Sustainable Development* 37(5). doi: 10.1007/s13593-017-0457-3.

Landry, J. B., and R. R. Golden. 2018. "In Situ Effects of Shoreline Type and Watershed Land Use on Submerged Aquatic Vegetation Habitat Quality in the Chesapeake and Mid-Atlantic Coastal Bays." *Estuaries and Coasts* 41:S101–13. doi: 10.1007/s12237-017-0316-0.

Law, N., K. Boomer, J. Christie, S. Jackson, E. McLaughlin, G. Noe, R. Roseen, S. Strano, and D. Wardrop. 2020. *Nontidal Wetland Creation, Rehabilitation and Enhancement: Recommendations of the Wetland Expert Panel for the Nitrogen, Phosphorus and Sediment Effectiveness Estimates for Nontidal Wetland Best Management Practices (BMPs).* Approved by CBP WQGIT.

Lee, S., A. M. Sadeghi, I.-Y. Yeo, G. W. McCarty, and W. D. Hively. 2017. "Assessing the Impacts of Future Climate Conditions on the Effectiveness of Winter Cover Crops in Reducing Nitrate Loads into the Chesapeake Bay Watershed Using SWAT Model." *Transactions of the American Society of Agricultural and Biological Engineers* 60(6):19391955.

Lee, S., I.-Y. Yeo, A. M. Sadeghi, G. W. McCarty, W. Hively, M. W. Lang, and A. Sharifi. 2018. "Comparative Analyses of Hydrological Responses of Two Adjacent Watersheds to Climate

Variability and Change Using the SWAT Model.” *Hydrology and Earth System Sciences* 22:689708.

Lefcheck, J. S., R. J. Orth, W. C. Dennison, D. J. Wilcox, R. R. Murphy, J. Keisman, C. Gurbisz, M. Hannam, J. B. Landry, K. A. Moore, C. J. Patrick, J. Testa, D. E. Weller, and R. A. Batiuk. 2018. “Long-Term Nutrient Reductions Lead to the Unprecedented Recovery of a Temperate Coastal Region.” *Proceedings of the National Academy of Sciences* 115(14):3658–62. doi: 10.1073/pnas.1715798115.

Leonardi, N., I. Camacina, C. Donatelli, N. K. Ganju, A. J. Plater, M. Schuerch, and S. Temmerman. 2018. “Dynamic Interactions between Coastal Storms and Salt Marshes: A Review.” *Geomorphology* 301:92–107. doi: 10.1016/j.geomorph.2017.11.001.

Lintern, A., L. McPhillips, B. Winfrey, J. Duncan, and C. Grady. 2020. “Best Management Practices for Diffuse Nutrient Pollution: Wicked Problems Across Urban and Agricultural Watersheds.” *Environmental Science & Technology* 54(15):9159–74. doi: 10.1021/acs.est.9b07511.

Liu, X., X. Zhang, and M. Zhang. 2008. “Major Factors Influencing the Efficacy of Vegetated Buffers on Sediment Trapping: A Review and Analysis.” *J Environ Qual* 37(5):1667–74. doi: 10.2134/jeq2007.0437.

Liu, Y., B. A. Engel, D. C. Flanagan, M. W. Gitau, S. K. McMillan, and I. Chaubey. 2017. “A Review on Effectiveness of Best Management Practices in Improving Hydrology and Water Quality: Needs and Opportunities.” *Sci Total Environ* 601–602:580–93. doi: 10.1016/j.scitotenv.2017.05.212.

Liu, Z., S. Fagherazzi, and B. Cui. 2021. “Success of Coastal Wetlands Restoration Is Driven by Sediment Availability.” *Zenodo*. doi: 10.5281/zenodo.4452744.

Lu, H., R. B. Bryant, A. R. Buda, A. S. Collick, G. J. Folmar, and P. J. A. Kleinman. 2015. “Long-Term Trends in Climate and Hydrology in an Agricultural, Headwater Watershed of Central Pennsylvania, USA.” *Journal of Hydrology: Regional Studies* 4:713–31. doi: 10.1016/j.ejrh.2015.10.004.

Mack, R., J. S. Owen, A. X. Niemiera, and D. J. Sample. 2019. “Validation of Nursery and Greenhouse Best Management Practices through Scientific Evidence.” *HortTechnology* 29(6):700–715. doi: 10.21273/horttech04303-19.

Mallakpour, I., and G. Villarini. 2017. “Analysis of Changes in the Magnitude, Frequency, and Seasonality of Heavy Precipitation over the Contiguous USA.” *Theoretical and Applied Climatology* 130:345–63. doi: 10.1007/s00704-016-1881-z.

McClain, M. E., E. W. Boyer, C. L. Dent, S. E. Gergel, N. B. Grimm, P. M. Groffman, S. C. Hart, J. W. Harvey, C. A. Johnston, E. Mayorga, W. H. McDowell, and G. Pinay. 2003. “Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems.” *Ecosystems* 6(4):301–12. doi: 10.1007/s10021-003-0161-9.

Meals, D. W., S. A. Dressing, and T. E. Davenport. 2010. “Lag Time in Water Quality Response to Best Management Practices: A Review.” *Journal of Environmental Quality* 39(1):85–96. doi: 10.2134/jeq2009.0108.

Miller, L. S., J. La Peyre, and M. La Peyre. 2017. “Suitability of Oyster Restoration Sites along The Louisiana Coast: Examining Site and Stock X Site Interaction.” *Journal of Shellfish Research* 36(2):341–51. doi: 10.2983/035.036.0206.

Miro, M. E., A. T. DeGaetano, T. Lopez-Cantu, C. Samaras, M. Webber, and K. Romita Grocholski. 2021. *Developing Future Projected Intensity-Duration-Frequency (IDF) Curves: A Technical Report on Data, Methods, and IDF Curves for the Chesapeake Bay Watershed and Virginia*. Santa Monica, CA: RAND Corporation.

Modi, P. A., D. R. Fuka, and Z. M. Easton. 2021. "Impacts of Climate Change on Terrestrial Hydrological Components and Crop Water Use in the Chesapeake Bay Watershed." *Journal of Hydrology: Regional Studies* 35:100830. doi: 10.1016/j.ejrh.2021.100830.

Moglen, G. E., and G. E. Rios Vidal. 2014. "Climate Change and Storm Water Infrastructure in the Mid-Atlantic Region: Design Mismatch Coming?" *Journal of Hydrologic Engineering* 19(11):04014026. doi: 10.1061/(ASCE)HE.1943-5584.0000967.

Mondelaers, K., J. Aertsens, and G. Van Huylenbroeck. 2009. "A Meta-analysis of the Differences in Environmental Impacts between Organic and Conventional Farming." *British Food Journal*.

Moreno-Mateos, D., M. E. Power, F. A. Comin, and R. Yockteng. 2012. "Structural and Functional Loss in Restored Wetland Ecosystems." *PLoS Biol* 10(1):e1001247. doi: 10.1371/journal.pbio.1001247.

Moss, R. H., J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. van Vuuren, T. R. Carter, S. Emori, M. Kainuma, T. Kram, G. A. Meehl, J. F. B. Mitchell, N. Nakicenovic, K. Riahi, S. J. Smith, R. J. Stouffer, A. M. Thomson, J. P. Weyant, and T. J. Wilbanks. 2010. "The next Generation of Scenarios for Climate Change Research and Assessment." *Nature* 463(7282):747–56. doi: 10.1038/nature08823.

Muhling, B. A., C. F. Gaitán, C. A. Stock, V. S. Saba, D. Tommasi, and K. W. Dixon. 2018. "Potential Salinity and Temperature Futures for the Chesapeake Bay Using a Statistical Downscaling Spatial Disaggregation Framework." *Estuaries and Coasts* 41(2):349–72. doi: 10.1007/s12237-017-0280-8.

Murphy, R. R., E. Perry, J. Harcum, and J. Keisman. 2019. "A Generalized Additive Model Approach to Evaluating Water Quality: Chesapeake Bay Case Study." *Environmental Modelling & Software* 118:1–13. doi: 10.1016/j.envsoft.2019.03.027.

Najjar, R. G., C. R. Pyke, M. B. Adams, D. Breitburg, C. Hershner, M. Kemp, R. Howarth, M. R. Mulholland, M. Paolisso, D. Secor, K. Sellner, D. Wardrop, and R. Wood. 2010. "Potential Climate-Change Impacts on the Chesapeake Bay." *Estuarine, Coastal and Shelf Science* 86(1):1–20. doi: 10.1016/j.ecss.2009.09.026.

Najjar, R., L. Patterson, and S. Graham. 2009. "Climate Simulations of Major Estuarine Watersheds in the Mid-Atlantic Region of the US." *Climatic Change* 95(1):139–68. doi: 10.1007/s10584-008-9521-y.

Nakicenovic, N., and R. Swart. 2000. *Emissions Scenarios. A Special Report of IPCC Working Group III*. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Neff, R., H. Chang, C. G. Knight, R. G. Najjar, B. Yarnal, and H. A. Walker. 2000. "Impact of Climate Variation and Change on Mid-Atlantic Region Hydrology and Water Resources." *Climate Research* 14(3):207–18. doi: 10.3354/cr014207.

Noe, G. B., N. A. Bourg, K. W. Krauss, J. A. Duberstein, and C. R. Hupp. 2021. "Watershed and Estuarine Controls Both Influence Plant Community and Tree Growth Changes in Tidal Freshwater Forested Wetlands along Two U.S. Mid-Atlantic Rivers." *Forests* 12(9):1182. doi: 10.3390/f12091182.

Nummer, S. A., S. S. Qian, and R. D. Harmel. 2018. "A Meta-Analysis on the Effect of Agricultural Conservation Practices on Nutrient Loss." *J Environ Qual* 47(5):1172–78. doi: 10.2134/jeq2018.01.0036.

Ockenden, M. C., C. E. Deasy, C. McW. H. Benskin, K. J. Beven, S. Burke, A. L. Collins, R. Evans, P. D. Falloon, K. J. Forber, K. M. Hiscock, M. J. Hollaway, R. Kahana, C. J. A. Macleod, S. M. Reaney, M. A. Snell, M. L. Villamizar, C. Wearing, P. J. A. Withers, J. G. Zhou, and P. M. Haygarth. 2016. "Changing Climate and Nutrient Transfers: Evidence from High Temporal Resolution Concentration-Flow Dynamics in Headwater Catchments." *Science of The Total Environment* 548–549:325–39. doi: 10.1016/j.scitotenv.2015.12.086.

Ockenden, M. C., M. J. Hollaway, K. J. Beven, A. L. Collins, R. Evans, P. D. Falloon, K. J. Forber, K. M. Hiscock, R. Kahana, C. J. A. Macleod, W. Tych, M. L. Villamizar, C. Wearing, P. J. A. Withers, J. G. Zhou, P. A. Barker, S. Burke, J. E. Freer, P. J. Johnes, M. A. Snell, B. W. J. Surridge, and P. M. Haygarth. 2017. "Major Agricultural Changes Required to Mitigate Phosphorus Losses under Climate Change." *Nature Communications* 8(1):161. doi: 10.1038/s41467-017-00232-0.

O'Donnell, J. E. D. 2017. "Living Shorelines: A Review of Literature Relevant to New England Coasts." *Journal of Coastal Research* 33(2):435–51. doi: 10.2112/jcoastres-d-15-00184.1.

Osman, M., K. Wan Yusof, H. Takaijudin, H. W. Goh, M. Abdul Malek, N. A. Azizan, A. Ab. Ghani, and A. Sa'id Abdurrasheed. 2019. "A Review of Nitrogen Removal for Urban Stormwater Runoff in Bioretention System." *Sustainability* 11(19). doi: 10.3390/su11195415.

Park, J.-Y., Y.-S. Yu, S.-J. Hwang, C. Kim, and S.-J. Kim. 2014. "SWAT Modeling of Best Management Practices for Chungju Dam Watershed in South Korea under Future Climate Change Scenarios." *Paddy and Water Environment* 12(S1):65–75. doi: 10.1007/s10333-014-0424-4.

Parris, A. S., P. Bromirski, V. Burkett, D. R. Cayan, M. E. Culver 1963-, J. Hall, R. M. Horton, K. Knuuti, R. H. Moss, J. Obeysekera, A. H. Sallenger, and J. Weiss. 2012. "Global Sea Level Rise Scenarios for the United States National Climate Assessment" edited by N. O. and A. Administration. United States Climate Program Office,.

Parton, W. J., A. R. Mosier, D. S. Ojima, D. W. Valentine, D. S. Schimel, K. Weier, and A. E. Kulmala. 1996. "Generalized Model for N2 and N2O Production from Nitrification and Denitrification." *Global Biogeochemical Cycles* 10(3):401–12. doi: 10.1029/96GB01455.

Passeport, E., P. Vidon, K. J. Forshay, L. Harris, S. S. Kaushal, D. Q. Kellogg, J. Lazar, P. Mayer, and E. K. Stander. 2013. "Ecological Engineering Practices for the Reduction of Excess Nitrogen in Human-Influenced Landscapes: A Guide for Watershed Managers." *Environ Manage* 51(2):392–413. doi: 10.1007/s00267-012-9970-y.

Pelletier, M. C., J. Ebersole, K. Mulvaney, B. Rashleigh, M. N. Gutierrez, M. Chintala, A. Kuhn, M. Molina, M. Bagley, and C. Lane. 2020. "Resilience of Aquatic Systems: Review and Management Implications." *Aquatic Sciences* 82(2):44. doi: 10.1007/s00027-020-00717-z.

Penn, C., I. Chagas, A. Klimeski, and G. Lyngsie. 2017. "A Review of Phosphorus Removal Structures: How to Assess and Compare Their Performance." *Water* 9(8). doi: 10.3390/w9080583.

Peterjohn, W. T., and D. L. Correll. 1984. "Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of A Riparian Forest." *Ecology* 65(5):1466–75. doi: 10.2307/1939127.

Qiu, F. G., and Y. Wang. 2013. "Phosphorus Pollution Control by Stormwater Bioretention Systems." *Advanced Materials Research* 726–731:1817–22. doi: 10.4028/www.scientific.net/AMR.726-731.1817.

Qiu, J., Z. Shen, X. Hou, H. Xie, and G. Leng. 2020. "Evaluating the Performance of Conservation Practices under Climate Change Scenarios in the Miyun Reservoir Watershed, China." *Ecological Engineering* 143:105700. doi: 10.1016/j.ecoleng.2019.105700.

Quemada, M., M. Baranski, M. N. J. Nobel-de Lange, A. Vallejo, and J. M. Cooper. 2013. "Meta-Analysis of Strategies to Control Nitrate Leaching in Irrigated Agricultural Systems and Their Effects on Crop Yield." *Agriculture, Ecosystems & Environment* 174:1–10. doi: 10.1016/j.agee.2013.04.018.

Ranaivoson, L., K. Naudin, A. Ripoche, F. Affholder, L. Rabeharisoa, and M. Corbeels. 2017. "Agro-Ecological Functions of Crop Residues under Conservation Agriculture. A Review." *Agronomy for Sustainable Development* 37(4). doi: 10.1007/s13593-017-0432-z.

Renkenberger, J., H. Montas, P. T. Leisnham, V. Chanse, A. Shirmohammadi, A. Sadeghi, K. Brubaker, A. Rockler, T. Hutson, and D. Lansing. 2017. "Effectiveness of Best Management Practices with Changing Climate in a Maryland Watershed." *Transactions of the ASABE* 60(3):769–82. doi: 10.13031/trans.11691.

Renkenberger, J., H. Montas, P. T. Leisnham, V. Chanse, A. Shirmohammadi, A. Sadeghi, K. Brubaker, A. Rockler, T. Hutson, and D. Lansing. 2016. "Climate Change Impact on Critical Source Area Identification in a Maryland Watershed." *Transactions of the ASABE* 59(6):1803–19. doi: 10.13031/trans.59.11677.

Rice, K. C., D. L. Moyer, and A. L. Mills. 2017. "Riverine Discharges to Chesapeake Bay: Analysis of Long-Term (1927–2014) Records and Implications for Future Flows in the Chesapeake Bay Basin." *Journal of Environmental Management* 204(1):246–54. doi: 10.1016/j.jenvman.2017.08.057.

Ridge, J. T., A. B. Rodriguez, and F. J. Fodrie. 2017. "Salt Marsh and Fringing Oyster Reef Transgression in a Shallow Temperate Estuary: Implications for Restoration, Conservation and Blue Carbon." *Estuaries and Coasts* 40(4):1013–27. doi: 10.1007/s12237-016-0196-8.

Rob, C., L. De, and D. K. Reid. 2000. "Climate Variability, Climate Change and Water." *Climatic Change* 45:163–79.

Roldán, A., J. R. Salinas-García, M. M. Alguacil, and F. Caravaca. 2007. "Soil Sustainability Indicators Following Conservation Tillage Practices under Subtropical Maize and Bean Crops." *Soil and Tillage Research* 93(2):273–82. doi: 10.1016/j.still.2006.05.001.

Römkens, M. J. M., K. Helming, and S. N. Prasad. 2002. "Soil Erosion under Different Rainfall Intensities, Surface Roughness, and Soil Water Regimes." *CATENA* 46(2):103–23. doi: 10.1016/S0341-8162(01)00161-8.

Ross, A. C., and R. G. Najjar. 2019. "Evaluation of Methods for Selecting Climate Models to Simulate Future Hydrological Change." *Climatic Change* 157(3):407–28. doi: 10.1007/s10584-019-02512-8.

Ross, J. A., M. E. Herbert, S. P. Sowa, J. R. Frankenberger, K. W. King, S. F. Christopher, J. L. Tank, J. G. Arnold, M. J. White, and H. Yen. 2016. "A Synthesis and Comparative Evaluation of Factors Influencing the Effectiveness of Drainage Water Management." *Agricultural Water Management* 178:366–76. doi: 10.1016/j.agwat.2016.10.011.

Roy-Poirier, A., P. Champagne, and Y. Filion. 2010. "Review of Bioretention System Research and Design: Past, Present, and Future." *Journal of Environmental Engineering* 136(9):878–89. doi: 10.1061/(Asce)Ee.1943-7870.0000227.

Ryberg, K. R., J. D. Blomquist, L. A. Sprague, A. J. Sekellick, and J. L. Keisman. 2018. "Modeling Drivers of Phosphorus Loads in Chesapeake Bay Tributaries and Inferences about Long-Term Change." *Science of the Total Environment* 616–617:1423–30. doi: 10.1016/j.scitotenv.2017.10.173.

Schaefer, S. C., and M. Alber. 2007. "Temperature Controls a Latitudinal Gradient in the Proportion of Watershed Nitrogen Exported to Coastal Ecosystems." *Biogeochemistry* 85(3):333–46. doi: 10.1007/s10533-007-9144-9.

Schmidt, M. L., S. Sarkar, J. B. Butcher, T. E. Johnson, and S. H. Julius. 2019. "Agricultural Best Management Practice Sensitivity to Changing Air Temperature and Precipitation." *Transactions of the ASABE* 62(4):1021–33. doi: 10.13031/trans.13292.

Sekellick, A. J., O. H. Devereux, J. L. D. Keisman, J. S. Sweeney, and J. D. Blomquist. 2019. *Spatial and Temporal Patterns of Best Management Practice Implementation in the Chesapeake Bay Watershed, 1985–2014*. *Report*. 2018–5171. Reston, VA. doi: 10.3133/sir20185171.

Selbig, W. R., and R. T. Bannerman. 2008. *A Comparison of Runoff Quantity and Quality from Two Small Basins Undergoing Implementation of Conventional and Low-Impact-Development (LID) Strategies: Cross Plains, Wisconsin, Water Years 1999-2005*. *Report*. 2008–5008. doi: 10.3133/sir20085008.

Seong, C., and V. Sridhar. 2017. "Hydroclimatic Variability and Change in the Chesapeake Bay Watershed." *Journal of Water and Climate Change* 8(2):254–73. doi: 10.2166/wcc.2016.008.

Sharpley, A. N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. 2003. *Agricultural Phosphorus and Eutrophication Second Edition*. ARS–149. U.S. Department of Agriculture, Agricultural Research Service.

Shenk, G. W., G. Bhatt, R. Tian, C. F. Cerco, I. Bertani, and L. C. Linker. 2021. *Modeling Climate Change Effects on Chesapeake Water Quality Standards and Development of 2025 Planning Targets to Address Climate Change*. CBPO Publication Number 328-21. Annapolis, MD.

Sheppard, S. C., and G. J. Racz. 1984. "Effects of Soil Temperature on Phosphorus Extractability. i. Extractions and Plant Uptake of Soil and Fertilizer Phosphorus." *Canadian Journal of Soil Science* 64(2):241–54. doi: 10.4141/cjss84-025.

Sinha, E., and A. M. Michalak. 2016. "Precipitation Dominates Interannual Variability of Riverine Nitrogen Loading across the Continental United States." *Environmental Science & Technology* 50(23):12874–84. doi: 10.1021/acs.est.6b04455.

Smith, C. J., and P. M. Chalk. 2020. "The Role of 15N in Tracing N Dynamics in Agro-Ecosystems under Alternative Systems of Tillage Management: A Review." *Soil and Tillage Research* 197. doi: 10.1016/j.still.2019.104496.

Stephenson, K., C. Hershner, B. Benham, Z. Easton, J. Hanson, S. Julius, and E. Hinrichs. 2018. *Consideration of BMP Performance Uncertainty in Chesapeake Bay Program Implementation*. Edgewater, MD.

Sweeney, B. W., and J. D. Newbold. 2014. “Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review.” *JAWRA Journal of the American Water Resources Association* 50(3):560–84. doi: 10.1111/jawr.12203.

Sweet, W. V., R. Horton, R. E. Kopp, A. N. LeGrande, and A. Romanou. 2017. *Sea Level Rise. Climate Science Special Report: Fourth National Climate Assessment, Volume I*. U.S. Global Change Research Program. doi: 10.7930/J0VM49F2.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2012. “An Overview of CMIP5 and the Experiment Design.” *Bulletin of the American Meteorological Society* 93(4):485–98. doi: 10.1175/BAMS-D-11-00094.1.

Tyner, J. S., D. C. Yoder, B. J. Chomicki, and A. Tyagi. 2011. “A Review of Construction Site Best Management Practices for Erosion Control.” *Transactions of the ASABE* 54(2):441–50. doi: 10.13031/2013.36447.

Ullrich, A., and M. Volk. 2009. “Application of the Soil and Water Assessment Tool (SWAT) to Predict the Impact of Alternative Management Practices on Water Quality and Quantity.” *Agricultural Water Management* 96(8):1207–17. doi: 10.1016/j.agwat.2009.03.010.

USEPA. 2018. *Improving the Resilience of Best Management Practices In A Changing Environment: Urban Stormwater Modeling Studies (Final Report)*. EPA/600/R 17/469F. U.S. Environmental Protection Agency, Washington, D.C.

Valenca, R., H. Le, Y. Zu, T. M. Dittrich, D. C. W. Tsang, R. Datta, D. Sarkar, and S. K. Mohanty. 2021. “Nitrate Removal Uncertainty in Stormwater Control Measures: Is the Design or Climate a Culprit?” *Water Research* 190:116781. doi: 10.1016/j.watres.2020.116781.

Van Liew, M. W., S. Feng, and T. B. Pathak. 2012. “Climate Change Impacts on Streamflow, Water Quality, and Best Management Practices for the Shell and Logan Creek Watersheds in Nebraska, USA.” *International Journal of Agricultural and Biological Engineering* 5(1):13–34.

Vanuytrecht, E., D. Raes, P. Willems, and S. Geerts. 2012. “Quantifying Field-Scale Effects of Elevated Carbon Dioxide Concentration on Crops.” *Climate Research* 54(1):35–47. doi: 10.3354/cr01096.

Vidon, P., C. Allan, D. Burns, T. P. Duval, N. Gurwick, S. Inamdar, R. Lowrance, J. Okay, D. Scott, and S. Sebestyen. 2010. “Hot Spots and Hot Moments in Riparian Zones: Potential for Improved Water Quality Management1.” *JAWRA Journal of the American Water Resources Association* 46(2):278–98. doi: 10.1111/j.1752-1688.2010.00420.x.

Wagena, M. B., A. S. Collick, A. C. Ross, R. G. Najjar, B. Rau, A. R. Sommerlot, D. R. Fuka, P. J. A. Kleinman, and Z. M. Easton. 2018. “Impact of Climate Change and Climate Anomalies on Hydrologic and Biogeochemical Processes in an Agricultural Catchment of the Chesapeake Bay Watershed, USA.” *Science of The Total Environment* 637–638:1443–54. doi: 10.1016/j.scitotenv.2018.05.116.

Wagena, M. B., and Z. M. Easton. 2018. “Agricultural Conservation Practices Can Help Mitigate the Impact of Climate Change.” *Science of The Total Environment* 635:132–43. doi: 10.1016/j.scitotenv.2018.04.110.

Wallace, C. W., D. C. Flanagan, and B. A. Engel. 2017. “Quantifying the Effects of Conservation Practice Implementation on Predicted Runoff and Chemical Losses under Climate Change.” *Agricultural Water Management* 186:51–65. doi: 10.1016/j.agwat.2017.02.014.

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, and J. Willis. 2014. "Appendix 3: Climate Science Supplement." *Climate Change Impacts in the United States: The Third National Climate Assessment* 735–389. doi: doi:10.7930/J0KS6PHH.

Wang, P., L. Linker, H. Wang, G. Bhatt, G. Yactayo, K. Hinson, and R. Tian. 2017. "Assessing Water Quality of the Chesapeake Bay by the Impact of Sea Level Rise and Warming." *IOP Conference Series: Earth and Environmental Science* 82:012001. doi: 10.1088/1755-1315/82/1/012001.

Wetz, M. S., and D. W. Yoskowitz. 2013. "An 'Extreme' Future for Estuaries? Effects of Extreme Climatic Events on Estuarine Water Quality and Ecology." *Marine Pollution Bulletin* 69(1):7–18. doi: 10.1016/j.marpolbul.2013.01.020.

Wiggs, G. F. S., A. J. Baird, and R. J. Atherton. 2004. "The Dynamic Effects of Moisture on the Entrainment and Transport of Sand by Wind." *Aeolian Research: Processes, Instrumentation, Landforms and Palaeoenvironments* 59(1):13–30. doi: 10.1016/j.geomorph.2003.09.002.

Williams, M. R., G. Bhatt, S. Filoso, and G. Yactayo. 2017. "Stream Restoration Performance and Its Contribution to the Chesapeake Bay TMDL: Challenges Posed by Climate Change in Urban Areas." *Estuaries and Coasts* 40(5):1227–46. doi: 10.1007/s12237-017-0226-1.

Wolfe, D. W., A. T. DeGaetano, G. M. Peck, M. Carey, L. H. Ziska, J. Lea-Cox, A. R. Kemanian, M. P. Hoffmann, and D. Y. Hollinger. 2018. "Unique Challenges and Opportunities for Northeastern US Crop Production in a Changing Climate." *Climatic Change* 146(1):231–45. doi: 10.1007/s10584-017-2109-7.

Wood, D. 2021. *Vulnerability Analysis and Resilient Design Considerations for Stormwater Best Management Practices*. Chesapeake Stormwater Network.

Woznicki, S. A., and A. P. Nejadhashemi. 2011. "Sensitivity Analysis of Best Management Practices Under Climate Change Scenarios1." *JAWRA Journal of the American Water Resources Association* 48(1):90–112. doi: 10.1111/j.1752-1688.2011.00598.x.

Woznicki, S. A., A. P. Nejadhashemi, and C. M. Smith. 2011. "Assessing Best Management Practice Implementation Strategies under Climate Change Scenarios." *Transactions of the ASABE* 54(1):171–90. doi: 10.13031/2013.36272.

Woznicki, S. A., and P. A. Nejadhashemi. 2014. "Assessing Uncertainty in Best Management Practice Effectiveness under Future Climate Scenarios: ASSESSING UNCERTAINTY IN BEST MANAGEMENT PRACTICE EFFECTIVENESS." *Hydrological Processes* 28(4):2550–66. doi: 10.1002/hyp.9804.

Xia, L., S. K. Lam, D. Chen, J. Wang, Q. Tang, and X. Yan. 2017. "Can Knowledge-Based N Management Produce More Staple Grain with Lower Greenhouse Gas Emission and Reactive Nitrogen Pollution? A Meta-Analysis." *Glob Chang Biol* 23(5):1917–25. doi: 10.1111/gcb.13455.

Xia, Y., M. Zhang, D. C. W. Tsang, N. Geng, D. Lu, L. Zhu, A. D. Igalavithana, P. D. Dissanayake, J. Rinklebe, X. Yang, and Y. S. Ok. 2020. "Recent Advances in Control Technologies for Non-Point Source Pollution with Nitrogen and Phosphorous from Agricultural Runoff: Current Practices and Future Prospects." *Applied Biological Chemistry* 63(1). doi: 10.1186/s13765-020-0493-6.

Xu, Y., D. J. Bosch, M. B. Wagena, A. S. Collick, and Z. M. Easton. 2019. “Meeting Water Quality Goals by Spatial Targeting of Best Management Practices under Climate Change.” *Environmental Management* 63(2):173–84. doi: 10.1007/s00267-018-01133-8.

Yang, Y.-Y., and M. G. Lusk. 2018. “Nutrients in Urban Stormwater Runoff: Current State of the Science and Potential Mitigation Options.” *Current Pollution Reports* 4(2):112–27. doi: 10.1007/s40726-018-0087-7.

Yu, C., P. Duan, Z. Yu, and B. Gao. 2019. “Experimental and Model Investigations of Vegetative Filter Strips for Contaminant Removal: A Review.” *Ecological Engineering* 126:25–36. doi: 10.1016/j.ecoleng.2018.10.020.

Zhang, Q., R. R. Murphy, R. Tian, M. K. Forsyth, E. M. Trentacoste, J. Keisman, and P. J. Tango. 2018. “Chesapeake Bay’s Water Quality Condition Has Been Recovering: Insights from a Multimetric Indicator Assessment of Thirty Years of Tidal Monitoring Data.” *The Science of the Total Environment* 637–638:1617–25. doi: 10.1016/j.scitotenv.2018.05.025.

Zhang, X., X. Liu, M. Zhang, R. A. Dahlgren, and M. Eitzel. 2010. “A Review of Vegetated Buffers and a Meta-Analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution.” *J Environ Qual* 39(1):76–84. doi: 10.2134/jeq2008.0496.

Zhou, M., K. Butterbach-Bahl, H. Vereecken, and N. Brüggemann. 2017. “A Meta-Analysis of Soil Salinization Effects on Nitrogen Pools, Cycles and Fluxes in Coastal Ecosystems.” *Global Change Biology* 23(3):1338–52. doi: 10.1111/gcb.13430.

Appendix

Chesapeake Bay Total Maximum Daily Load

Achieving water quality standards is foundational to federal, state, and local efforts to restore the Chesapeake Bay living resources. While the 2014 Chesapeake Bay Agreement included 10 broad restoration goals, the Clean Water Act (CWA) creates a legal obligation to meet water quality standards (WQS) that include dissolved oxygen, chlorophyll-a, and water clarity criteria to achieve the Bay's designated uses for aquatic living resources.

Since the 1980s, the CBP has identified nutrients (nitrogen, N and phosphorus, P) as the primary stressors impacting Bay water quality (sediment, S, has since been added). The CBP uses a suite of models to predict how load reduction practices will result in achievement of WQS. The suite of models includes an air deposition model (predicting atmospheric N inputs to the watershed and the Bay), a land use model, and a watershed model. The watershed model uses estimates of nutrient inputs, land use, and weather conditions to estimate loads of nutrients and sediment delivered to the Bay. The watershed model is the primary way the CBP predicts the effect of point source and NPS load control efforts on the delivery of nutrients/sediment to the Bay. An estuarine water quality model predicts how water quality conditions in the Bay (e.g., DO concentrations) respond to nutrient/sediment loads. The CBP also uses the estuarine model to predict how compliance with water quality criteria changes under different water quality conditions.

The CBP jurisdictions develop watershed implementation plans (WIPs) that specify the control measures they will implement to meet nutrient and sediment load targets in the TMDL. The Bay watershed modeling framework is then used to predict whether the selected nutrient and sediment control practices will meet the jurisdictions load limits. The same Bay watershed model is also used as an accounting tool to record each jurisdictions' progress in implementing its chosen practices in reaching the nutrient and sediment targets established in the TMDL. In general, the CBP accounting framework counts point source loads as measured changes at the point source outfall while nonpoint source loads are estimated using the watershed model. For example, if a jurisdiction implements 100 stormwater BMPs (e.g., bioretention areas) in the lower Potomac, the Bay model generates estimates of the N, P, and S reductions produced by those 100 BMPs. When the local or state jurisdiction reports and verifies BMP installation, the CBP awards nutrient and sediment reduction credits. Only BMPs approved by the CBP and integrated into the watershed model can count toward achievement of the TMDL targets.

Jurisdiction efforts to achieve the TMDL rely on a variety of regulatory and voluntary policies and programs. Most jurisdictions impose numeric nutrient effluent limitations on point sources (e.g., municipal, and industrial wastewater treatment permits) above a certain size. With respect to non-point source loads, many jurisdictions have established numeric nutrient and sediment permits for municipal separate storm sewer systems (MS4s). MS4 permits in many states within the Chesapeake Bay region are unique in that they place numeric limits on urban NPS loads. Numeric MS4 permits represent a significant departure from traditional MS4 permits which were based on narrative rather than numeric requirements. Agricultural NPS pollution is the single largest contributor of nutrient and sediment loads to the Bay. WIPs specify agricultural NPS load reduction practices (i.e., best management practices, BMPs), that if implemented, are predicted to produce nutrient/sediment reductions.

Few water quality improvement efforts match the scope, scale, and complexity of the Chesapeake Bay. Federal, state, and local governments and citizens have spent billions of dollars to reduce nutrient and sediment loads to the Bay. Monitoring data show improvements in dissolved oxygen levels in the Bay, and submerged aquatic vegetation (SAV), an important Bay living resource, has expanded substantially in recent years (Lefcheck et al. 2018) , although anecdotal evidence collected in 2019 and 2020 (STAR, 2021) suggest SAV increases are not consistent. Yet, the rate of progress in achieving the desired water quality goals has been slow. The percent of the Bay estimated to be in attainment of water quality standards has increased from 26.5% to 40% between 1985 and 2016 (Zhang et al. 2018), and monitoring data show that observed in-stream nutrient load reductions do not reflect predicted reductions in some parts of the Bay watershed, particularly in watersheds dominated by nonpoint source (NPS) pollution (Ator et al. 2019, 2020; Keisman et al. 2018).

Table A1:
https://docs.google.com/spreadsheets/d/1qx6cT5FOyqgWpeNqAYePgkEItvPlo6me11DwsX2vCcs/edit?usp=sharing

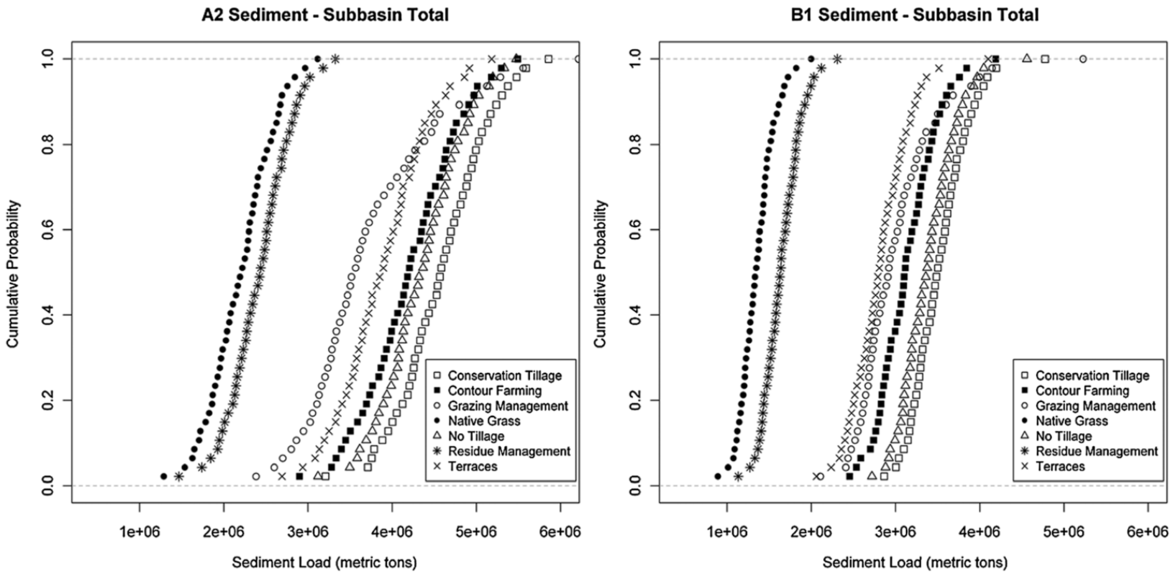


Figure A1. More pronounced climate change creates greater BMP performance variability and affects the relative effectiveness of different practices. Sediment cumulative distributions of A2 and B1 (one of every five simulation points displayed). Source: Woznicki et al. 2011.

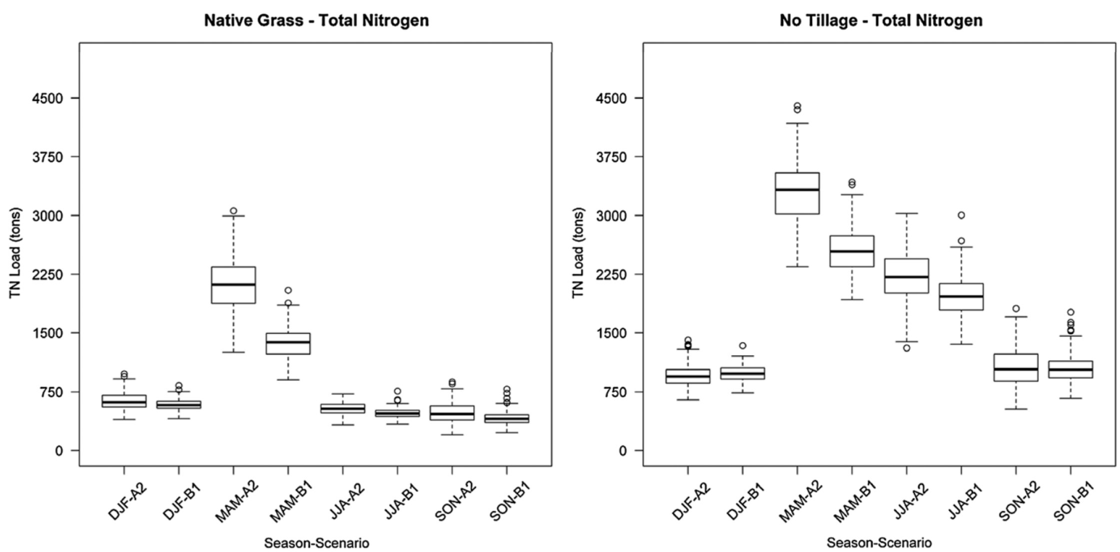


Figure A2. Seasonal distribution of BMP variability changes under different future climate conditions. TP cumulative distributions of A2 and B1 (one of every five simulation points displayed). Source: Woznicki et al. 2011.

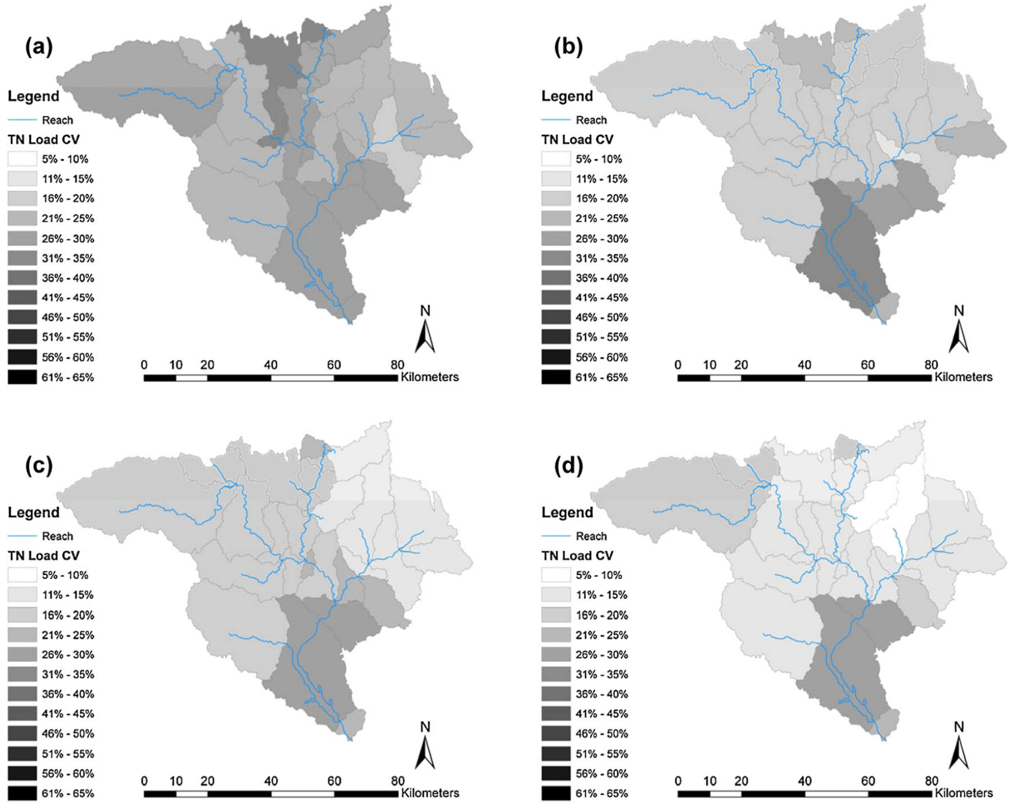


Figure A3. Spatial distribution of BMP variability under historical and future climate. Subbasin level TN coefficient of variation (CV) for (a) native grass A2, (b) native grass B1, (c) no tillage A2, (d) no tillage B1. Source: Woznicki et al. 2011.

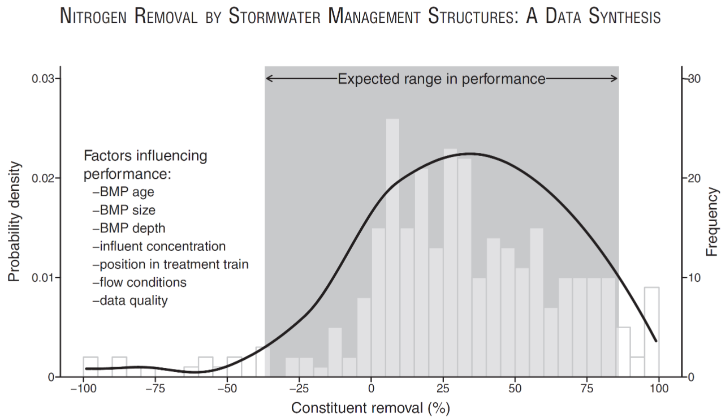
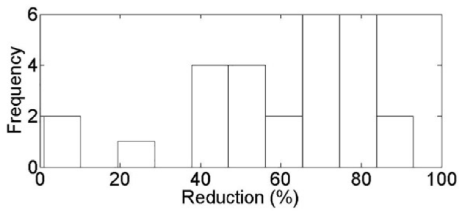
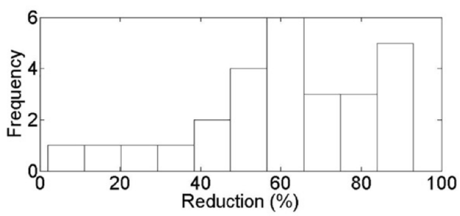


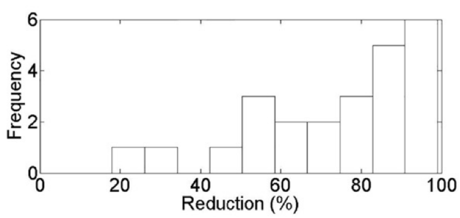
Figure A4. Probability density function for stormwater BMPs. Source: Koch et al. (2014).



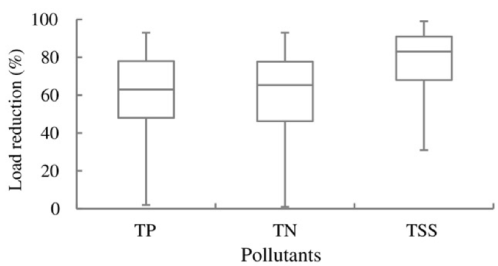
(a) TN



(b) TP



(c) Sediment



(d) Boxplots of vegetated filter strip efficiencies

Figure A5. Probability distributions of stormwater and agricultural BMPs derived from empirical measurements. Source: Liu et al. (2017).