NUTRIENT BALANCES IN SOUTHERASTERN MASSACHUSETTS CRANBERRY BOGS

FINAL REPORT

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Executive Summary

Cranberry bogs make up an important part of the landscape, economics, and cultural heritage of southeastern Massachusetts. Because cranberry bogs use ponds and rivers as water sources and as discharge points, the control of runoff of both nitrogen (N) and phosphorus (P) to surface waters from cranberry farming is a critical concern for the health and management of fresh and estuarine waters in watersheds where cranberry bogs occur. This study quantified the movement of N and P into and out of three cranberry bogs in the Weweantic and Wareham River Watersheds over a water year and annual cropping cycle from October 2015 through September 2016. Bogs were standard wetland-type bogs that represented the predominant bog type in Massachusetts. Measurements of water inputs and outputs (precipitation, harvest floods, winter floods, frost irrigation, summer irrigation, and non-flood baseflow discharges during periods when water was not actively pumped) included all phases of bog management. Groundwater exchanges were estimated by difference from the bog surface water budget. The concentrations of dissolved and particulate forms of N and P moving in different water flows were sampled and then combined with water volumes to produce annual estimates of the total N and P moving into and out of each bog. Automated samplers were used to capture dynamic N and P concentrations during harvest and winter floods and to collect composite samples of water leaving bogs during non-flood baseflow discharge. Groundwater wells upgradient of each bog were sampled and combined with estimates of the volume of net groundwater inflow to estimate groundwater N and P inputs. Total annual N and P fluxes were calculated both as fluvial fluxes (total exchanges carried by precipitation, surface water and groundwater) and total fluxes that included inputs in fertilizer and outputs in harvested berries and vegetation.

Water budgets varied widely among bogs. Two bogs showed net movement of groundwater into the bog and one bog had net water flow into groundwater. Groundwater inflow in one bog was very high. Water output in non-flood baseflows made up 53 to 69% of total water outflow. Output of water in harvest floods made up 7 to 14% of annual water export and output of water in winter floods made up 9 to 15% of total water export. Output of water during summer rainstorms was small and less than 3% of water export.

Bogs also varied widely in patterns of N retention or export. Two bogs exhibited small net N imports (0.1 and 2.0 kg N ha^{-1}) in fluvial exchanges and one bog exhibited substantial net N export (12.6 kg N ha^{-1}). Between 73 and 77% of all N exported from all bogs exited in surface water during non-flood baseflows. The N exported in harvest floods was 14 to 20% of annual fluvial N export but only 3 to 9% of annual fluvial N export occurred in winter floods. Almost no N was exported following growing season rainstorms but this likely did not represent the potential for N export by this mechanism because rainfall during summer 2016 was only 22% of the long-term average.

Bogs varied less in patterns of P retention and loss. Bogs exported between 2.1 and 4.5 kg P ha^{-1} in fluvial exchanges. Between 55 and 81% of all P exported from bogs exited in surface water during non-flood baseflows. The P exported in harvest floods was 15 to 31% of annual fluvial P export and P export in winter floods was 1 to 14% of fluvial P export. Less than 2% of total fluvial P export occurred following growing season rains in any bog.

The variation in both the magnitude and direction of net N exchanges among bogs makes it difficult to determine a "typical" N exchange for cranberry bogs in Massachusetts coastal watersheds. This variation occurred even though the amount of N fertilizer applied and the

amount and timing of water applied for crop management were generally similar across all bogs. This variability of net N exchange likely arose from the hydro-geographical setting in which the bogs occurred. The variation in the magnitude and direction of P exchanges was lower and depended less on bog setting. The combination of detailed hydrological and chemical measurements from which our annual estimates were derived provided increased confidence in the magnitude of these exchanges. The estimates of export of N and P reported here for harvest and winter floods and for total annual N and P export were generally lower than reported by previous studies. On a per area basis, the N inputs to coastal watershed from fluvial exchanges with cranberry bogs were generally modest compared with other potential watershed N sources. This study focused on exchanges with individual bogs and did not estimate the potential total effects of the total area of cranberry bogs within watersheds on receiving waters. This would require estimation of other factors such as total cranberry bog area, attenuation of N within river networks between bog outlets and receiving waters, and the relative effects of different dissolved and particulate N forms on biological responses within receiving waters.

This study examined the typical "wetland" type cranberry bogs that make up approximately 70% of total cranberry bog area in Massachusetts. It did not examine the newer "upland" bogs that now make up about 22% of total area. These typically contain drainage tiles, are generally planted with hybrid cranberry varieties that have higher yields and receive higher amounts of fertilizer, and could possibly differ in fluvial N and P exchanges.

Given the finding that most annual export of N and P occurred in surface water flows during times that water was not actively pumped onto or released from bogs, water management specifically aimed at N and P removal from the small but steady outflow of surface water that occurs from most bogs during non-flood periods could be beneficial. Such management might include additional storage time in ponds or increased naturalization of stream channels to enhance N uptake and denitrification.

Introduction

Cranberry bogs make up an important part of the landscape and cultural heritage of southeastern Massachusetts (Thomas 1990). The farming of American cranberry (*Vaccinium microcarpon* Aiton) is economically important and cranberries rank first in value of Massachusetts' food crops (MA EOEEA 2017a). Approximately 23% of the nation's cranberry crop is produced within Massachusetts, and almost all of this production occurs in coastal watersheds in southeastern Massachusetts (USDA 2014). Cranberry agriculture is intimately connected to natural waterways because cranberry production requires water sources for irrigation and for flooding of bogs for berry harvest and for protection from winter damage. Although American cranberry is a naturally occurring wetland plant, it grows best in relatively dry soils that require irrigation for spring frost protection and summer moisture (Eck 1990).

Cranberry bogs use pon ds and rivers as water sources and as discharge points, and water is typically moved by pumping or by gravity directly between cranberry bogs and surface waters. Water is used to flood bogs in September or October to facilitate fall berry harvest and to remove fallen leaves, and during cold periods in winter to protect vines from freezing and desiccation (DeMoranville 2008). Surface water is typically sprayed onto the bog surface through a sprinkler system during cold periods in spring to protect vines from frost, and during dry periods in summer to provide supplemental water. Nitrogen (N) is the main controlling factor in cranberry nutrition, but both nitrogen and phosphorus (P) are applied to bogs as components of best management practices (Ghantous et al. 2017).

The close connection between cranberry bogs and local water bodies poses a challenge for water resources managers because control of runoff of both N and P to surface waters is critical to maintaining the health of regional surface waters. In southeastern Massachusetts, N is the principal driver of eutrophication of estuarine waters and increasing loads of N delivered to estuaries causes a cascade of events including oxygen depletion, loss of submersed aquatic vegetation, and decreases of fish and shellfish (Valiela et al. 1997, Deegan et al. 2002, Howarth and Marino 2006). These trends are broadly typical of those in U.S. coastal waters (Nixon 1995, Bricker et al. 2007). In the freshwater portions of southeastern Massachusetts watersheds, P has a greater effect on algae production than N (Caraco et al. 1987). The major controlling role of P in limiting algal production in fresh waters is well established (Volenweider et al. 1974, Oglesby 1977, Peterson et al. 1993), although recent evidence indicates that N and P are co-limiting in many North American lakes, including on Cape Cod, Massachusetts (Elser et al. 2007, Kniffin et al. 2009, Paerl et al. 2016). Dissolved organic N is also transported to coastal water (Kroeger et al. 2006) but is less bioavailable and plays a less certain role in controlling aquatic production.

Eutrophication of surface waters is a significant concern in the 146 km^2 Weweantic and 90 km^2 Wareham River watersheds in which most Massachusetts cranberry farming occurs. Water quality in the Weweantic and Wareham Rivers and their associated estuaries suffers from nutrient over enrichment that is derived from multiple sources including cranberry bogs, septic systems, storm water, and lawn fertilizer. Both estuaries are listed on the State's Integrated List of Impaired Waters as impaired because of nutrient loads (MA GIS 2014). Both estuaries experienced eelgrass loss and have high summer phytoplankton biomass and oxygen depletion that are characteristic of high nitrogen loads (Buzzards Bay Coalition 2016).

Previous studies indicate that cranberry bogs contribute to the nutrient loads of rivers, but nutrient losses from cranberry bogs and the relative importance of cranberry agriculture compared with other nutrient sources in watersheds are poorly known. While a large number of studies exist that demonstrate the effects of septic systems on water quality for Massachusetts coastal waters (MA Estuaries Project 2017), pollution managers currently have very limited information on nutrient inputs from cranberry bogs. Calculation of cranberry bog nutrient contributions to surface waters is challenging for several reasons. First, bogs have a wide variety of connections to surface waters, they often have multiple surface water intake and release points, and they can both receive and contribute to groundwater as well as surface waters. Bogs occupy different positions in the landscape and can have very different background concentrations of N and P in entering groundwater and surface waters. Second, nutrient exchanges between bogs and surface waters during floods can change during flooding events (Kennedy 2015). Accurately characterizing nutrient exchanges during floods requires dynamic sampling of concentrations of released water during floods. Third, new evidence suggests that N releases during heavy rains during the summer growing season are substantial and can comprise a larger portion of annual N releases than fall harvest floods (Kennedy et al. 2016).

One previous study of a cranberry bog in Bourne, MA found net annual N losses of 24 kg N ha^{-1} and annual net P losses of 11 kg P ha^{-1} (Howes and Teal 1995). Another study of six different bogs over two years that was designed to identify P dynamics, showed net P losses of 1 to 7 kg ha^{-1} yr^{-1} and net N losses ranging from 4 to about 16 kg ha^{-1} yr^{-1} (DeMoranville and Howes 2005). We previously quantified fluxes onto and off of six cranberry bogs during harvest and winter floods from surface water inputs and outputs. We found that the surface water fluxes of total dissolved N in harvest and winter floods varied widely across bogs from negative (more N entered than exited) to positive (more N exited than entered) and ranged from -2.6 to 3.8 kg N ha^{-1} during harvest floods, and from -1.3 to 11.9 kg N ha^{-1} during winter floods (Town of Carver et al. 2015). Fluxes of total P ranged from 0.1 to 6.4 kg P ha^{-1} during harvest floods and from -4 to 0.4 kg P ha^{-1} during winter floods (Town of Carver et al. 2015). These fluxes were lower than calculated by Howes and Teal (1995), potentially because the bogs in the Town of Carver (2015) study were typical bogs that were physically separated from surface waters by levees and water control structures, while the Howes and Teal (1995) study involved a bog with a now uncommon "flow-through" configuration in which bogs were not physically separated from an adjacent river channel and flooding was achieved by temporarily blocking the river channel. These factors, and large differences in the magnitude and even the net direction of flows among studies, make it difficult to develop the comprehensive management plans for eliminating sources of nutrient pollution that are required by the Clean Water Act.

Changes to regional climate could influence water management strategies and nutrient exchanges in cranberry agricultural systems because bog operations have strong connections with surface waters. For example, the greater total rainfall predicted with climate change for the northeastern U.S. (Horton et al. 2014) could reduce demand for summer irrigation, but a predicted increase in the number of extreme rainfalls could increase total water and nutrient export that occurs during these events.

The objective of this project was to provide a better estimate of N and P exchanges in cranberry bogs in the Weweantic and Wareham River Watersheds and to use the results to recommend potential strategies for reducing nutrient releases from cranberry bogs to watersheds. This study combined: (1) dynamic and frequent sampling of water and nutrients moved in and out of bogs during fall harvest and winter floods, (2) continuous sampling of water and nutrients in water released from bogs during non-flood periods, and (3) dynamic sampling of water discharged from bogs following rainstorms that occurred during the growing season. The project was a partnership among the Buzzards Bay Coalition (Coalition), the University of Massachusetts Cranberry Station (Cranberry Station), the Marine Biological Laboratory (MBL), and individual cranberry growers.

Site Descriptions and Bog Management

The project selected three bogs for detailed study from September 2015 to September 2016. The bogs were selected because they were configured and previously instrumented to allow accurate quantification of water and nutrient concentrations and fluxes. At the project outset, a list of potential sites was compiled by representatives of the Cranberry Station, MBL, the Coalition, and Cape Cod Cranberry Growers Association (Town of Carver et al. 2015). Criteria that influenced selection included: (1) bogs that had a single bed with a clear inflow and outflow (bog systems with inter-connected beds were avoided because of the difficulty of isolating water inputs and releases), (2) bogs that received historical and current fertilizer and water management typical of the region, and (3) bogs that had owners and managers willing to provide physical access, notice of water movement dates, and information on historical and current bog fertilizer and water management. The three bogs were typical of those created originally from wetlands. They had irregular shapes and were separated from surface waters by dikes and water control structures. They were not flow-through bogs, nor were they newer-style bogs that are typically rectangular, and often created from uplands and with artificial drainage below the bog bed.

Bogs were located in the towns of Carver, Plymouth and Wareham, MA (Fig. 1). The size of the study bogs ranged from 1.17 to 2.91 ha (2.89 to 7.18 acres) (Table 1). Detailed maps of the study bogs and sampling locations are included in Appendix A.

Rocky Pond Bog is a solitary 1.70 ha (4.20 acre) bog within the Myles Standish State Forest fed from an irrigation pump at Rocky Pond. The cranberry variety is Stevens and the bog was renovated (replanted) in 2002. Floodwaters are pumped from Rocky Pond to the bog. The outlet of the bog is a channel that runs south where it is joined from the outlet to another nearby bog, and then to Federal Pond approximately 130 meters downstream of the outlet from the study bog. The water from the Rocky Pond bog travels through a series of channels, ponds, and streams before reaching the Weweantic River Reservoir approximately five miles away.

White Springs Bog is a solitary 2.91 ha (7.18 acre) bog located within the Myles Standish State Forest fed by an inlet channel from Barrett Pond. The White Springs Bog has not been physically renovated in many decades but is planted with a mixture of the Early Black variety and the newer hybrid Mullica Queen. Water is released from a water control structure on Barrett Pond to flood the bog. Water exits the bog from a channel on the southwest corner of the bog that extends approximately 150 meters before going under East Head Road and then Cranberry Road, where it connects to a stream that feeds into the Weweantic River.

State Bog is a system of five bogs at the Cranberry Station in East Wareham, MA fed by Spectacle Pond. The bogs are flooded by pumping water from Spectacle Pond into a channel that runs along the south edge of the bogs. Water then flows by gravity through water control structures into the individual bogs. The flow exiting the bogs returns to Spectacle Pond via the same canal. This study used the 1.17 ha (2.89 acre) Bed 3 of this bog system. The cranberry variety in Bed 3 is Stevens and the bog was renovated in 2006.

Growers provided records of fertilizer applications rates and dates, and bog crop yields. Nutrient applications and water manipulations in the bogs were documented by bog managers. Managers selected fertilizer rates based on the nitrogen requirements of the bogs (determined by evaluation of plant growth, color, crop potential, and cultivar). Fertilizer was applied in spring during leaf expansion and in summer during fruit set but not in fall. This was consistent with regional practice (UMass Cranberry Station 2016). All the bogs received between 35 and 37 kg ha^{-1} of N fertilizer and 5 and 11 kg ha^{-1} of P fertilizer in 2015 and 2016 (Table 2). Nitrogen fertilizer was applied as ammonium or urea and during periods of active growth before fruit set in keeping with typical practice (Davenport et al. 2000). Phosphorus was applied as phosphate in combination with N also in keeping with typical practice (Roper et al. 2004). Across all bogs, the mean rate of fertilizer application during the study years was similar to the average of the preceding seven years except for State Bog, which received less P than the longer-term average in 2016. The mean yield of cranberries across all bogs varied from 16.1 to 32.0 Mt ha^{-1} (143 to 285 bbl ac^{-1}) in 2015 and 2016 (Table 2). Yields varied more widely in 2016 than 2015. Yields in Rocky Pond Bog were lower than the longer-term average in 2015 but higher in 2016. Yields in White Springs and State Bogs in both years were higher than the longer-term average (Table 2).

Harvest floods occurred between September 30 and November 1 in 2015 and lasted from 7 to 14 days (Table 3). Winter floods were more variable and occurred between January 4 and January 28 and lasted from as little as 17 days to as long as 24 days (Table 3). At Rocky Pond and White Springs Bogs, boards were also placed into water control structures to fill bog ditches and raise water level, but water did not reach the bog surface. These boards were in place for as little as 7 days to as long as 33 days (Table 3). Growing season storms of sufficient magnitude to trigger surface flows occurred April 7-8, July 17-18 and August 10-11 at Rocky Pond Bog, April 7-8 and August 10-12 at White Springs Bog and April 7, May 30-31 and July 5-6 at State Bog.

Methods

We quantified water and nutrient inputs and outputs to each bog with measurements that included all flooding events when bog managers actively moved water in and out of bogs and the remaining “non-flood” periods when less dynamic water movement occurred without pumping or manipulation of water control structures.

Instrumentation

Bogs were instrumented with the following:

- A minimum of three shallow groundwater sampling wells upgradient and three shallow groundwater wells downgradient of the bog bed. Sampling of collected groundwater allowed estimates of the concentrations of solutes in groundwater entering or leaving the bog;
- A water level datalogger (Onset Hobo) that recorded water level in the bog ditch every 15 minutes. The elevation of the logger was surveyed against a local benchmark to determine water level in bog ditches and over the bog surface. A reference Onset Hobo water level logger recorded ambient air pressure at the Cranberry Station;
- A water control flume in the outlet channel or a flow meter in the inlet and outlet water level control structure. In Rocky Pond and White Springs Bogs, flumes were located in the outlet channels and outfitted with Onset Hobo water level dataloggers that recorded channel stage every 15 minutes. The stage records were converted to instantaneous water flow based on flume

dimensions. At State Bog, an acoustic Doppler area velocity meter (Isco/Teledyne 2150) installed on the bog bed water control structure directly measured water flux;

- At Rocky Pond and State Bogs, pumps directly recorded water pumped onto bogs during floods. At White Springs Bog, because the concrete inlet channel did not allow installation of a flume in a manner that bog managers determined would allow adequate movement of floodwaters onto the bog, we estimated the volume of inflowing floodwater from a combination of water height over the bog surface and the area of the bog platform and bog ditches;
- Isco 6712 automatic water samplers in locations to sample inflowing and outflowing water during floods. These were programmed to collect up to 24 samples during bog flooding and floodwater release. If waters were still high and being release after all bottles were collected, samplers were reset to continue collecting;
- Isco 6712 automatic water samplers on outlet channels or structures. These were programmed to collect 200 ml of water daily for four days into individual 1L sample bottles. Each 800 ml sample represented a composite of water during those four days;
- A separate Isco 6712 water sampler located on the outlet channel and outfitted with an automatic tipping bucket rain gage (Isco 674). The tipping bucket was programmed to initiate sampling after accumulating 5 mm of precipitation in 5 min;
- A NOAA National Climatic Data Center station in East Wareham, MA at the Cranberry Station (station ID GHCND:USC00192451) provided daily temperature and precipitation.

Water fluxes

We developed annual water budgets for each bog that accounted for all water that moved in natural or managed flows (Equation 1). The budgets accounted for all water that entered bogs in: (1) precipitation, (2) surface water during harvest floods ($_{hf}$), winter floods ($_{wf}$) and in irrigation water ($_{ir}$). The budgets accounted for water that exited bogs in (1) evapotranspiration (ET), or (2) surface water during harvest floods, winter floods, non-flood baseflow periods ($_{nf}$) and growing season rainstorms ($_{st}$) (Table 4). We separated water used for irrigation into irrigation for spring frost protection, summer supplemental moisture provided through sprinklers, and supplemental moisture provided from the subsurface by flooding bog ditches. We estimated the net annual exchange with groundwater (GW) for each bog by the difference between all inflowing and outflowing water flows.

Equation 1: $P + SW_{in:hf} + SW_{in:wf} + SW_{ir} + GW = ET + SW_{out:hf} + SW_{out:wf} + SW_{out:nf} + SW_{out:st}$

Daily precipitation was obtained for the NOAA National Climatic Data Center station at the Cranberry Station in East Wareham, MA. We determined the volumes of surface water pumped into Rocky Pond Bog and State Bog for harvest and winter floods and for irrigation from a metered pump. We measured the volume of water moved onto White Springs Bog from bog water level and bog area. We could not reliably estimate irrigation volumes from the pump records at White Springs, so we used the measured irrigation volumes from nearby Rocky Pond Bog, which lies in a similar microclimatic setting, as an estimate of the irrigation water input.

We estimated daily evapotranspiration (ET) from the vegetated bog surfaces using the Priestly-Taylor equation adapted for Massachusetts cranberry bogs (Priestly and Taylor 1972). Input parameters were daily maximum and minimum temperature, daily solar radiation, and daily maximum and minimum relative humidity, which were obtained from the Kingston, Rhode Island U.S. Climate Observing Reference Network station. We also included a crop coefficient of 0.83 for cranberries, based on two studies in Wisconsin (Bland et al. 1996, Vanderleest and Bland 2016). The crop coefficient relates measured ET to modeled ET and is assumed to be linear based on Bland et al. (1996).

We calculated directly the volume of surface water discharged from Rocky Pond and White Springs Bogs from a continuous record of stage height at the outlet flumes (Gore 2007). We calculated the surface water discharged from State Bog from the flow meter on the outlet structure (Kennedy 2015). At White Springs, the high volume of water exiting for several hours during mid flood release was higher than could be measured by the flume, so water fluxes during this period were determined from change in water volume on the bog determined from the continuous record of bog water level and bog area. Net annual groundwater exchange was determined as the difference between total annual water outputs and total annual water inputs as has been done for other cranberry bogs (Kennedy 2015). The annual water balance was calculated from October 1, 2015 to September 30, 2016 for Rocky Pond and White Springs Bogs. The water balance was calculated from September 30, 2015 to September 29, 2016 for State Bog because the harvest flood was initiated on September 30, 2015 and this captured the harvest and winter floods within the same water year.

The surface area of each bog was determined from 2014 Google Earth satellite imagery. Area was measured to both the inner and outer edges of bog ditches to allow calculation of the area of ditches and of the growing bed. We used total bog area that included the bed and ditches. Field measurements were made of the depth of the bog ditches and the elevation difference between the bottom of the ditches and the top of the growing bed.

Groundwater wells

In 2012 and 2013 we installed a minimum of three permanent wells for the collection of shallow groundwater adjacent to each bog on both the upgradient and downgradient sides. These collected inflowing and outflowing groundwater. These consisted of 3.8 cm (1.5 in) stainless steel drive points (AMS, Inc.) with a screen and 0.64 cm (0.25 in) outside diameter nylon tubing that extended to the surface. The micro-wells were inserted with a 1.6 cm (0.625 in) diameter pipe that was driven to about 60 cm below the water table and then withdrawn, leaving the points and tubing in place. Holes were backfilled with native soil. Wells were sampled by pumping them dry with a peristaltic pump (Geotech, Inc), allowing them to refill, then extracting samples.

Nutrient concentration sampling

Sampling of nutrients from surface waters began during the fall 2015 harvest flood. During floods, surface water samples of inflowing and outflowing water were collected with Isco samplers at intervals that ranged from every 20 minutes to 6 hours depending on flood duration. Samplers were programmed to sample more frequently during the initial stages of flooding and water release when water volumes were greater and less frequently near the end of flooding and release when water volumes were smaller. The duration of flooding and floodwater releases varied within and among bogs and between harvest and winter floods. Isco samplers were deployed for up to 8 days during harvest and winter floods.

Sampling of non-flood periods began after the 2015 harvest flood. During non-flood periods, Isco samplers collected 200 ml daily from the outlet channel or structure. Samples over four days were placed in the same 1L bottle to create 4-day composite samples. Because samplers for composite sampling were deployed for periods of up to three weeks, each Isco bottle contained

10 ml of 1N H_2SO_4 as a preservative. We conducted composite sampling from September 2015 to January 2016 and from March to May 2016. It was not possible to sample during periods when temperatures were regularly below zero because Isco sample lines froze and led to loss of battery power to the sampler. This freezing during sampling of winter floods led to occasionally missing samples. Isco samplers for composite sampling were deployed for up to eight days. Concentrations for unsampled periods were estimated from the mean concentration during the three composite (12-day) periods both before and after the sampling gap.

Groundwater wells were sampled between September 2012 and May 2016. Each well yielded between 3 and 13 samples during this time depending on groundwater levels.

Grab samples of all waters collected in the field were kept on ice and then transported to the MBL for processing on the same day they were collected. Samples for NH_4^+, NO_3, and PO_4^{3-} (soluble reactive phosphate) were filtered through 47 mm Whatman GFF filters. Subsamples for NH_4^+, NO_3^-, PO_4^{3-} (soluble reactive phosphate) and total dissolved nitrogen (TDN) were immediately frozen. For analysis of particulate organic carbon and nitrogen (POC and PON), a known volume of approximately 100 to 200 ml was filtered under low vacuum through pre-combusted 25 mm Whatman GF/F filters and oven dried at 60 ^oC. PON was not analyzed from groundwater wells because particulates collected from filtered groundwater represented sediments from the well rather than particulate N transported in groundwater. Total P from wells represented PO_4^{3-} and dissolved organic P but not particulate P.

We sampled periods following heavy rains during the growing season beginning on April 1, 2016 by placing Isco samplers equipped with tipping bucket rain gages on the outflowing bog water control structures. The rain gages were programmed to initiate sampling when rain exceeded 5 mm in 60 minutes. This allowed sampling of heavy rains but avoided sampling of light rains that would not trigger substantial increases in bog surface water outputs. We defined the period following a rain event as the storm hydrograph until the return to baseflow. Rainfall volumes for each storm were recorded from the Isco tipping bucket. PON samples from the first two storms at White Springs Bog were lost.

We collected a total of 413 samples of surface water during floods, 137 composite surface water samples during non-flood periods, 174 groundwater samples, 213 samples of surface water following rain events, and 6 additional grab samples from irrigation source waters (Table 5).

Laboratory nutrient analyses

Water samples were analyzed for particulate organic carbon (POC), particulate organic nitrogen (PON) (surface water samples only), ammonium (NH_4^+), nitrate+nitrite (hereafter referred to as NO_3^-), total dissolved nitrogen (TDN), soluble reactive phosphorus (PO_4^{3-}) and total phosphorus (TP).

All analyses were performed at the Ecosystems Center of the MBL. Ammonium was analyzed colorimetrically using the indophenol method. Nitrate + nitrite was analyzed colorimetrically by copper-cadmium reduction on a Lachat autoanalyzer. TDN was analyzed using a digestion with persulfate digestion to NO_3^- and subsquent analyzsis of NO_3^- by copper-cadmium reduction on a Lachat AutoAnalyzer. Dissolved organic nitrogen (DON) was calculated as TN minus (NH_4^+ + NO_3^-). The PO_4^{3-} samples were analyzed as soluble reactive P (SRP) colorimetrically on a Lachat autoanalyzer. TP was analyzed by digestion with persulfate to PO_4^{3-} and subsequent analysis of PO_4^{3-} on a Lachat autoanalyzer. Filters for POC and PON analysis were analyzed by combustion in a Thermo Scientific Flash 2000 NC Analyzer. Detection limits were 0.25 μM (0.004 mg L^{-1}) for NO_3^- + NO^{2-}, 0.5 μM (0.007 mg L^{-1}) for NH_4^+, 1 μM (0.014 mg L^{-1}) for TDN, 10 μg/l (0.01 mg L^{-1}) for PON, 0.25 μM (0.004 mg L^{-1}) for SRP, and 0.25 μM (0.004 mg L^{-1}) for TP. The methods utilized are described in detail in the Quality Assurance Project Plan (QAPP) for this project dated September 9, 2015 (Appendix 1).

Data analysis—solute and particulate concentrations

For groundwater, we plotted mean solute concentrations across all up- or downgradient wells for each bog for each sampling date. For surface waters during floods, we plotted concentrations of each solute or particulate over time for each bog and each flood. This allowed quantification of total nutrient movement and interpretation of mechanisms of exchange between the flooded bog platform and surface waters among bogs. For surface waters released from bogs during non-flood periods, we plotted changes in concentrations over time to detect seasonal patterns and differences in surface water concentrations among bogs. For surface waters following rain events, we plotted concentrations of each solute or particulate over time for each bog and each event. This allowed quantification of nutrient movement and interpretation of mechanisms and thresholds for export during rain events.

Data analysis—fluxes

We calculated the input of N to the bogs from the concentration of N in precipitation and rainfall volume measured at the Cranberry Station. The concentration of N in precipitation was determined from the National Atmospheric Deposition Program (NADP) station in Truro, MA (NTN Site MA01), where N concentrations were typically measured weekly. We estimated mass inputs of N in precipitation to the study bogs from the 2010 to 2015 average N concentrations measured at Site MA01 for a particular week multiplied by the volume of precipitation measured for that week at the Cranberry Station. We assumed the concentration of P in rainwater was zero based on very low concentrations reported for global assessments that included the eastern U.S. (Mahowald et al. 2008, Vet et al. 2014). The concentration of DON in precipitation was estimated as 0.455 of dissolved inorganic N (DIN) based on measurements of DON and DIN on Cape Cod (Bowen and Valiela 2000).

We calculated the amount of N and P that moved into and out of the bogs in surface water during the following phases of the cranberry cultivation cycle: (1) harvest and winter floods, when large amounts of water are moved onto and off of bogs by active management, (2) irrigation for spring frost protection and summer supplemental moisture, (3) non-flood baseflow periods when water levels are maintained with water control structures but water typically leaves as surface water flow, and (4) following heavy rain events when water potentially leaves the bog as surface water flows. For floods, the mass of different forms of N and P inputs and outputs were calculated from the product of the volume of water moved and N and P concentrations. For samples below detection limits we set the concentration equal to half the detection limit. We summed fluxes to daily values and then summed the daily values for the days that flood-related water movement occurred to obtain total mass flux per flood. Inputs of different forms of N and P in irrigation water were calculated from the volume of water moved and the N and P concentrations in the source water matched to the time of irrigation. During non-flood periods, we calculated the outputs of different forms of N from the concentrations of the four-day composite samples and total water discharge during the four-day period. Because PO_4^{3-} could not be reliably determined separately from TP in the acid-preserved samples collected by the Isco automatic samplers, we estimated only output fluxes of TP for the non-flood composite sampling periods.

Following rain events, we calculated fluxes as the product of water flow and the concentrations of N and P measured during the storm hydrography by the Isco sampler. For Rocky Pond and White Springs Bogs, water flow was determined from the water level record at the outlet flumes and for State Bog water flow was determined directly from the flow meter.

For Rocky Pond and White Springs Bogs, which had net annual groundwater movement into the bogs, we estimated the annual input or output of different forms of N and P moving in groundwater from the volume of water moving into or out of the bog (determined from the annual water balance) multiplied by the median concentration of N and P in upgradient shallow groundwater. We use median concentrations because the distributions of solute concentrations in groundwater were skewed toward low or zero concentrations. At Rocky Pond Bog, all upgradient wells (RP 6, 13, 14, 15, 16 and 17) had similar dissolved N and P concentrations and we used the median solute concentrations across all wells to calculate annual groundwater input flux. At White Springs Bog, of the two wells that most likely captured upgradient groundwater (WS 10, 12), one (WS 10) showed evidence of elevated NH_4^+ concentrations in shallow groundwater that can occur from bog flooding (Kennedy 2015). We therefore used the median N and P concentrations in the well at White Springs most likely to represent background upgradient shallow groundwater (WS 12) to calculate annual groundwater input flux. At State Bog, which had net groundwater movement out of the bog, we used the median concentration of N and P in surface water during the harvest and winter floods, when movement into the groundwater was most likely to occur (Kennedy 2015), and we weighted the surface water concentrations by the days in harvest and winter floods.

We determined annual fertilizer inputs from farm records. We used fertilizer application rate in 2016 to calculate total N and P balances because 2016 growing season applications occurred during the October 2015 to September 2016 water year. We determined N and P export in harvested cranberries from farm records of the wet berry harvest, dry weight equivalent of berries, and an N content in dried berries of 0.45% and P content of 0.07% (Hart et al. 2015). We also estimated the amount of N and P in "trash" (leaves) removed inadvertently during the harvest and a trash N content of 0.7% and content of 0.1% (Hart et al. 2015). We used the 2015 harvest to calculate total N and P balances because it occurred during the studied water year.

We determined the relative contribution of different source waters and outlet waters to the total inflowing and outflowing fluxes for different N and P forms and for total N and P. We also determined the importance of different periods (harvest flood, winter floods, non-flood periods, rainstorms) to inflowing and outflowing N and P fluxes in surface waters. We separated fluxes during all periods into fluxes carried by surface and groundwater (fluvial fluxes) from nutrient fluxes that included inputs in fertilizer and outputs in harvested cranberries (total fluxes).

Results

Water levels and water discharge

Bog water levels were below the bog platforms for most of the year and were elevated during the fall harvest and winter floods (Fig. 2). Water levels and the timing of this pattern were similar in all bogs and reflected regional bog management practices. Discharge in bog outlet channels at Rocky Pond and White Springs Bogs was lowest during bog flooding when boards were placed in bog outlet water control structures to hold flow, and highest during flood releases (Fig. 2). Both Rocky Pond and White Springs Bogs were in locations that had regular groundwater inputs and the outlets of these bogs had regular but low surface water discharge at most times (Fig. 2). State Bog was in a different position relative to groundwater and had little water discharge through the outlet water control structure under most conditions (Fig. 2).

Annual water balance

Precipitation during the study year was 1,164 to 1,184 mm (Table 6). Total rainfall during June, July and August 2016 was 60 mm. Inflowing surface water used annually for harvest floods ranged from 391 to 646 mm (Table 6) and surface water used annually for winter floods ranged from 239 to 847 mm (Table 6). Water released by harvest floods annually ranged from 218 to 693 mm (Table 6) and the water discharged annually during winter floods ranged from 285 to 1,443 mm (Table 6). Bogs differed more widely in the amount of annual groundwater exchanges. Annual net groundwater discharge into Rocky Pond Bog was 5,970 mm while State Bog was a source of 145 mm to the groundwater (Table 6). Total annual surface water inputs ranged from 1,338 mm in White Springs Bog to 2,201 mm in Rocky Pond Bog. Total outputs to surface water ranged more widely, from 2,273 mm in State Bog to 8,639 mm in Rocky Pond Bog. Annual flow during non-flood periods ranged from 1,684 mm in State Bog to 6,446 mm in Rocky Pond Bog and made up the largest amount of water exiting all bogs (Table 6). In all cases, 136 mm or less of water exited bogs annually in growing season rainstorms (Table 6).

Harvest floods made up between 7 to 15% of annual water inputs and 7 to 14% of annual water outputs (Table 7). Winter floods made up 7 to 19% of annual water inputs and 9 to 15% of annual water outputs (Table 7). Groundwater made up the 64% of annual water input in Rocky Pond Bog and 32% of the input to White Springs Bog, but there was no net groundwater input into State Bog (Table 7). Net groundwater output made up 6% of total water output from State Bog. Non-flood baseflow comprised 53 to 69% of all water exiting bogs (Table 7). In contrast, growing season rainstorms made up less than 4% of the water exiting any bog (Table 7).

Solute and particulate concentrations during harvest floods

Concentrations of NO_3^- in inflowing harvest floodwater were below 0.02 mg N L^{-1} in all bogs and varied very little over time (Fig. 3A). Concentrations of NO_3^- in outflowing harvest floodwaters of Rocky Pond and State Bogs increased approximately mid-way through the flood release period and were highest at the end of the floods (Fig. 3A). Concentrations of NO_3^- in outflowing harvest floodwaters of White Springs Bog did not vary predictably during the flood release (Fig. 3A).

Concentrations of NH_4^+ in inflowing harvest floodwater were also below 0.02 mg N L^{-1} L in all bogs and also varied very little over time (Fig. 3B). Concentrations of NH_4^+ in the outflowing harvest floodwaters of all bogs increased approximately halfway through the flood release and highest concentrations of NH_4^+ occurred at the end of the flood (Fig. 3B).

Concentrations of DON in inflowing harvest floodwater ranged from approximately 0.1 to 0.4 mg N L^{-1} and varied little over time in all bogs (Fig. 3C). Concentrations of DON in inflowing harvest floodwater were as much as 10-fold higher than concentrations of NO_3^- and NH_4^+ (Fig. 3C). In all bogs, concentrations of DON in outflowing harvest floodwaters increased during the flood release and peak DON concentrations occurred from approximately the first third of the flood release in Rocky Pond Bog to the last third of the flood release in State Bog

(Fig. 3C). DON concentrations were low at the end of the flood release in all bogs (Fig. 3C). The magnitude of the peak DON concentration varied, from about two times the ending concentration in White Springs Bog to about five times the ending concentration in State Bog.

Concentrations of PON in inflowing harvest floodwaters were approximately 0.1 mg N L^{-1} and varied little over time in all bogs (Fig. 3D). Concentrations of PON in outflowing harvest floodwaters increased during the middle portion of the flood release in White Springs and State Bogs and the peak concentration of about 0.5 to 0.6 mg N L^{-1} was similar in all bogs (Fig. 3D).

Concentrations of PO_4^{3-} in inflowing harvest floodwaters were low and varied little over time in all bogs (Fig. 4A). Concentrations of PO_4^{3-} in outflowing harvest floodwaters increased during the early flood release period in Rocky Pond and White Springs Bogs but not in State Bog (Fig. 4A). Concentrations of PO_4^{3-} in all bogs at the end of the flood release periods were low and similar to inflowing floodwater (Fig. 4A).

Concentrations of TP in inflowing harvest floodwaters were low and varied little across all bogs (Fig. 4B). Concentrations of TP in outflowing harvest floodwaters increased during the early flood release period in Rocky Pond and White Springs Bogs but not in State Bog (Fig. 4B). Patterns of TP concentrations in outflowing harvest floodwaters closely mirrored patterns of PO_4^{3-} concentrations.

Solute concentrations during winter floods

Concentrations of NO_3^- in inflowing winter floodwater varied relatively little and were below 0.04 mg N L^{-1} in all bogs (Fig. 5A). Concentrations of NO_3^- in outflowing winter floodwaters of Rocky Pond Bogs were higher than in inflowing floodwaters in Rocky Pond Bog but were similar to inflowing floodwaters at White Springs and State Bogs (Fig. 5A). Concentrations of NO_3^- in winter flood outflowing water were similar to those in harvest flood outflowing water.

Concentrations of NH_4^+ in inflowing winter floodwater were uniformly low in all bogs (Fig. 5B). Concentrations of NH_4^+ in the outflowing winter floodwaters was higher than inflowing floodwaters and reached peak concentrations of 0.2 to 0.5 mg N L^{-1} (Fig. 5B). State Bog had the highest NH_4^+ concentrations in outflowing winter floodwaters. Peak NH_4^+ concentrations occurred during the middle of the winter flood release in all bogs (Fig. 5B). Concentrations of NH_4^+ in outflowing winter floodwater were similar to those in outflowing harvest floodwater in Rocky Pond and White Springs Bogs but higher than those in outflowing harvest floodwater in State Bog (peak concentrations of 0.5 compared with 0.2 mg N L^{-1}).

Concentrations of DON in inflowing winter floodwater were uniformly low and between 0.1 and 0.2 mg N L^{-1} (Fig. 5C). Concentrations of DON in inflowing harvest floodwater were often five-fold higher than concentrations of NO_3^- and NH_4^+ (Fig. 5C). With the exception of four samples during the peak harvest flood release in State Bog, concentrations of DON in outflowing winter floodwater were similar (0.1 to 0.5 mg N L^{-1}) to those in outflowing harvest floodwater. Concentrations of PON in both inflowing and outflowing winter floodwaters generally ranged between 0.1 and 0.3 mg N L^{-1} and did not differ between flood directions (Fig. 5D).

Concentrations of PO_4^{3-} in inflowing winter floodwaters were extremely low and varied little in all bogs (Fig. 6A). Concentrations of PO_4^{3-} in outflowing winter harvest floodwaters were very similar to concentrations in inflowing water in Rocky Pond and State Bogs but about six to eight times higher in White Springs Bog (Fig. 6A). Concentrations of PO_4^{3-} in outflowing winter floodwater in White Springs Bog peaked early during the flood release (Fig. 6A).

Solute concentrations during non-flood periods

Concentrations of NH_4^+, NO_3^- and DON in outflowing surface water collected in four-day composite samples varied very little in Rocky Pond and White Springs Bogs (Fig. 7). The concentrations of NO_3^- in outflowing surface water in State Bog were also very low, but the concentrations of NH_4^+ and DON were higher and more variable (Fig. 7). Concentrations of NO_3^-, NH_4^+, DON and PON measured in grab samples matched concentrations measured in the automatic collectors in all bogs (Fig. 7).

Concentrations of TP in outflowing surface water collected in four-day composite samples varied between 0.01 and 0.08 mg P L^{-1} across all bogs (Fig. 8). Concentrations were low in winter and tended to increase in mid summer (Fig. 8). Concentrations of PO_4^{3-} measured in grab samples were consistently lower than concentrations measured in the automatic collectors (Fig. 8). This likely occurred because of the oxidation of dissolved or particulate organic P to PO_4^{3-} during holding in the automatic sampler (in which samples were preserved with 1N H_2SO_4 to pH at 2). Concentrations of TP measured in grab samples were similar to concentrations measured in the automatic collectors (Fig. 8).

Solute concentrations following rain events

Concentrations of NO_3^-, NH_4^+, DON and PON varied across a relatively narrow range following summer rainstorms (Fig. 9). The concentration of NO_3^- was slightly elevated early in some but not all storm hydrographs in Rocky Pond and State Bogs (Fig. 9). Concentrations of PO_4^{3-} and TP did not vary in Rocky Pond and State Bogs but were highest in the middle of the storm hydrograph in two out of three storms in White Springs Bog (Fig. 10).

Solute concentrations in groundwater

The median concentrations of NO_3^- ranged from below detection (<0.004 mg N L^{-1}) to 0.44 mg N L^{-1} in upgradient groundwater and from below detection to 0.20 mg N L^{-1} in downgradient groundwater (Table 8). The median concentrations of NO_3^- in downgradient groundwater were nearly identical to that in upgradient groundwater at Rocky Pond and White Springs Bogs and lower than that in upgradient groundwater at State Bog (Table 8).

The median concentrations of NH_4^+ ranged from 0.01 to 0.02 mg N L^{-1} in upgradient groundwater and from 0.04 to 0.09 mg N L^{-1} in downgradient groundwater (Table 8). The greatest difference between median upgradient and downgradient NH_4^+ concentrations occurred in White Springs Bog where the NH_4^+ concentration was 0.09 mg N L^{-1} downgradient and 0.01 mg N L^{-1} upgradient (Table 8). The NH_4^+ concentration at Rocky Pond Bog was also higher in upgradient compared with downgradient groundwater (Table 8).

The median concentrations of DON ranged from 0.03 to 0.16 mg N L^{-1} in upgradient groundwater and from 0.10 to 0.16 mg N L^{-1} in downgradient groundwater (Table 8). The median concentrations of DON in upgradient and downgradient groundwater were very similar at all bogs (Table 8).

The median concentrations of PO_4^{3-} in upgradient and downgradient groundwater were very low and below limits of detection in all bogs (Table 9). The median concentrations of organic P were higher than concentrations of PO_4^{3-} but were also low. Organic P concentrations were very similar in upgradient and downgradient groundwater in Rocky Pond and State Bogs but 0.017

mg P L^{-1} in downgradient groundwater compared with 0.007 mg P L^{-1} in upgradient groundwater in White Springs Bog (Table 9).

The median concentrations of NO_3^- in upgradient and downgradient groundwater varied very little over time in Rocky Pond and White Springs Bogs or in upgradient groundwater at State Bog (Fig. 11). In contrast, at State Bog, median NO_3^- concentrations in downgradient groundwater varied by a factor of about four and were highest in fall and winter (Fig. 11). The median concentrations of NH_4^+ in upgradient and downgradient groundwater varied very little over time in any bog (Fig. 11). The median concentrations of DON in upgradient and downgradient groundwater varied very little over time in Rocky Pond and White Springs Bogs and in upgradient groundwater at State Bog (Fig. 11). The median concentration of DON in downgradient groundwater at State Bog was elevated following one fall flood (Fig. 11). There were no general patterns associated with the timing of bog flooding for any of the dissolved N forms in either upgradient or downgradient groundwater.

The concentrations of PO_4^{3-} in upgradient and downgradient groundwater varied little over time at State Bog but were higher downgradient in September and October at White Springs Bog and Rocky Pond Bogs (Fig. 12). The median concentrations of organic P in upgradient ground water varied little across all bogs (Fig. 12). The median concentrations of organic P in downgradient groundwater also varied little at State Bog but were elevated at three sampling dates in September and October in White Springs Bog and one sampling date in October in Rocky Pond Bog (Fig. 12). There were no general patterns associated with the timing of bog flooding for either dissolved P form in either upgradient or downgradient groundwater.

Annual N and P fluvial inputs and outputs in precipitation, surface and groundwater

Total annual fluvial N inputs to bogs ranged from 24.7 kg N ha^{-1} in Rocky Pond Bog (Table 10), to 13.6 kg N ha^{-1} in White Springs Bog (Table 11) to 17.8 kg N ha^{-1} in State Bog (Table 12). N input in precipitation of 8.8 kg N ha^{-1} comprised a large portion of fluvial N input in all bogs. Annual net inputs of N in groundwater varied widely from 9.12 kg N ha^{-1} in Rocky Pond Bog to 1.36 kg N ha^{-1} in White Springs Bog to no N net input in State Bog where there was no net groundwater input. Precipitation made up 37 to 65% of fluvial N inputs, surface water 25 to 50% and groundwater 0 to 37% of fluvial N inputs to all bogs (Table 13). Precipitation was a smaller relative source of N to Rocky Pond Bog where the input of groundwater and therefore the input of N in groundwater were greater. Harvest floods accounted for 5 to 15% of N inputs across all bogs, winter floods accounted for only 1 to 4% of fluvial N inputs, and irrigation accounted for 8 to 38% of fluvial N inputs (Table 14).

Total annual fluvial N outputs ranged from bogs 37.3 kg N ha^{-1} in Rocky Pond Bog (Table 10), 11.6 kg N ha^{-1} in White Spring Bog (Table 11) and 17.7 kg N ha^{-1} in State Bog (Table 12). Surface water outflow accounted for 94 to 100% of all fluvial N outflows (Table 13). Net output flow of N to groundwater only occurred in State Bog and was 1.13 kg N ha^{-1} (Table 12). The largest fluvial outputs of N from all bogs occurred in surface water that flowed out during non-flood baseflow periods. These N outputs ranged from 28.7 kg N ha^{-1} in Rocky Pond Bog (Table 10), to 8.45 kg N ha^{-1} in White Springs Bog (Table 11), to 12.2 kg N ha^{-1} in State Bog (Table 12). Total N outputs in surface water made up 100% of total fluvial N outputs in Rocky Pond and White Springs Bogs and 94% of total fluvial N outputs in State Bog (Table 13). Total N outputs in non-flood flows were 73 to 77% of total fluvial N outputs across all bogs (Table 14). Growing season storms made up 2% or less of total fluvial N outputs (Table 14).

Total annual fluvial P inputs to bogs ranged from 1.99 kg P ha^{-1} in Rocky Pond Bog (Table 10), to 0.54 kg P ha^{-1} in White Springs Bog (Table 11) to 0.45 kg P ha^{-1} in State Bog (Table 12). Organic P accounted for by far the largest portion of P inputs in all cases. Groundwater was the largest source of fluvial P input to Rocky Pond and White Springs Bogs. This occurred despite low P concentrations in groundwater because P concentrations in inflowing surface water were even lower. There was no net groundwater input to State Bog and therefore no P input from groundwater. Groundwater made up 71% of fluvial P inputs to Rocky Pond Bog and 44% of fluvial P inputs to White Springs Bog (Table 13). Harvest floods made up between 7 and 56% of fluvial P inputs but winter floods made up only 4 to 9% of fluvial P inputs (Table 14). Irrigation made up 11 to 40% of fluvial P inputs (Table 14).

Total annual fluvial P outputs fell within a narrow range from 4.15 kg P ha^{-1} in Rocky Pond Bog (Table 10), to 4.99 kg P ha^{-1} from White Springs Bog (Table 11), and 2.80 kg P ha^{-1} from State Bog (Table 12). Surface water accounted for 93 to 100% of total fluvial P outputs (Table 13). The largest amount of P was exported in non-flood baseflows and these accounted for 55 to 81% of fluvial P export (Table 14). Harvest floods accounted for 15 to 31% of fluvial P outputs, winter floods accounted for 1 to 14%, and growing season storms 2% or less (Table 14).

The annual net fluvial fluxes of N varied widely among bogs from export of 12.67 kg N ha^{-1} from Rocky Pond Bog (Table 10) to retention or removal of 2.22 kg N ha^{-1} in White Springs Bog (Table 11) and 0.08 kg N ha^{-1} from State Bog (Table 12). The net annual fluvial fluxes of P varied less, from export of 2.16 kg P ha^{-1} from Rocky Pond Bog (Table 10), 4.45 kg P ha^{-1} from White Springs Bog (Table 11), and 2.35 kg P ha^{-1} from State Bog (Table 12).

Solute input and output balances including fertilizer and removal in cranberry harvest

Annual fertilizer inputs of 34.7 to 36.2 kg N ha^{-1} and 4.9 to 10.8 kg P ha^{-1} were the largest single inputs to all bogs (Fig. 13). Export during harvest of N and P in berries and trash was the single largest N and P export from all bogs (Fig. 13). One bog had net total N export and two bogs had net N retention or loss. Rocky Pond Bog exported 6.2 kg N ha^{-1} more than entered (Table 10). White Springs Bog retained or lost 4.5 kg N ha^{-1} (Table 11) and State Bog retained or lost 5.3 kg N ha^{-1} (Table 12). One bog had net P export and two bogs had net P retention. Rocky Pond Bog retained 4.2 kg P ha^{-1} (Table 10), White Springs Bog exported 2.7 kg P ha^{-1} (Table 11), and State Bog retained 1.8 kg P ha^{-1} (Table 12). Net annual imbalances for P, and the variability among P retention and loss, were smaller and less variable for P than for N.

Discussion

Bog characteristics

The bogs selected for this study were of a size, configuration, age and condition typical of cranberry farms in the region. The bogs also received typical water management that included flooding for fall harvest and winter frost protection, spring irrigation for frost protection, and summer irrigation for supplemental moisture. Approximately 90% of Massachusetts cranberry bogs use flooding for harvest and winter vine protection (DeMoranville 2008). The duration of the harvest and winter floods varied based on the time required to move water onto and off the bog, the availability of equipment, manpower and weather. Despite these differences in timing and duration of floods, all fell within the range of standard practices for Massachusetts cranberry bogs (UMass Cranberry Station 2016).

The cranberry varieties planted in the studied bogs were two of the three most widespread in Massachusetts. The cranberry variety Stevens in Rocky Pond Bog and State Bog was planted on 24% of Massachusetts cranberry bog area in 2014 and the variety Early Black on White Springs Bog was planted on 27% of Massachusetts bog area (Cannon and Sandler 2014). The cranberry variety Howes, which did not occur on the bogs we studied, made up an additional 24% of Massachusetts bog area. The newer Mullica Queen variety that was present in White Springs made up 1.4% of Massachusetts bog area in 2014. No other single variety covered more than 6.5% of total bog area in Massachusetts.

All the bogs received relatively similar and typical fertilizer application rates in the years preceding and during this study. Rates of annual N fertilizer application to bogs (35 to 36 kg N ha^{-1}) fell within the range of 28 to 45 kg N ha^{-1} that is recommended for most bogs in southeastern MA but toward the lower end of the range of 39 to 56 kg N ha^{-1} recommended for the Stevens variety (UMass Cranberry Station 2016). The rates of annual P fertilizer application (5 to 11 kg P ha^{-1}) fell in the range of up to 11 kg P ha^{-1} recommended for established bogs that do show P deficiency in tissue tests (UMass Cranberry Station 2016). Rates of fertilizer application to a bog in any year typically depend on the age and condition of cranberry vines.

The cranberry yields across the three study bogs of 16.0 to 32.0 Mt ha^{-1} (143 to 285 barrels ac^{-1}) in 2015 and 2016 spanned a wide range. The average yields across the three bogs in both years of approximately 24 Mt ha^{-1} (214 bbl ac^{-1}) was close to the Massachusetts statewide 2015 yield of 199 bbl ac^{-1} (USDA 2016). The similar yield in 2015 compared with past years in Rocky Pond Bog was consistent with the last renovation of Rocky Pond Bog in 2000. Higher yields in 2015 in White Springs and State Bogs compared with past years were consistent with the presence of the higher-yielding Mullica Queen variety in White Springs Bog and renovation of State Bog in 2006. There was no evidence that the patterns of nutrient concentration observed in this study were the result of unusual or atypical bog management. The three bogs examined in this study did not encompass the full range of cranberry bog types and bog management that occur in MA coastal watersheds. This study did not consider the less common "flow through" bogs in which bog beds are not physically separated from surface water bodies by earthen dikes. Flow-through bogs now represent a relatively small and declining proportion of all cranberry bogs in operation in MA. While the area of flow-through bogs in Massachusetts is not precisely known, it is now likely in the range of 10% or less (BBNEP 2016). This study also did not consider newer "upland" style bogs that are more typically rectangular, often created from uplands, commonly with artificial tile drainage below the bog bed, and planted with newer hybrid cranberry varieties. This style of bog represented about 22% of 3,244 ha (8,016 ac) of Massachusetts cranberry bogs managed by respondents to a 2016 survey (DeMoranville et al. 2016). While the bog type that we studied predominates current Massachusetts cranberry bog area, the area of upland bogs is currently increasing. Of 699 ha (1,726 ac) reported tiled in 2016, 43% of those were installed since 2012, and growers planned to install tile on an additional 140 ha (347 ac) in 2016-2017 (DeMoranville et al. 2016).

Water budget

Cranberry bogs share a characteristic with wetlands in that they have complex and differing hydrological connections with surface and groundwater. Estimation of water budgets for these features requires a combination of direct measurements of precipitation and surface water flows, modeled estimates of ET and estimates of groundwater exchanges that are most feasibly estimated by difference (Mitch and Gosselink 2007).

Precipitation of 1,164 to 1,184 mm measured during the water year was only slightly below the 1960-2014 average of 1,259 measured at nearby Lakeville, MA. Precipitation was slightly higher in the water year for State Bog because that water year was adjusted earlier by one day to include the initiation of the harvest flood and there was 20 mm of precipitation on that day. We modeled ET with a model specifically developed for cranberry bogs in Wisconsin but adapted to Massachusetts using locally measured rainfall, temperature, humidity and solar radiation as model drivers. There is no standard method for estimating ET from wetlands because it is difficult to capture the effects of vegetation structure and water table variation that can influence ET (Drexler et al. 2004, Seidecki et al. 2016). Our estimates of ET of 0 to 5.22 mm day^{-1} were similar or slightly lower than those measured in natural wetlands at somewhat similar latitudes. Kim and Verna (1996) measured ET of 0.2 to 4.8 mm day^{-1} in a Minnesota *Sphagnum* dominated fen, Lafleur et al. (2005) measured ET of 0.2 to 5 mm day^{-1} in peat shrubland in Ontario, Canada, and Siedlecki et al. (2016) measured ET of 0.3 to 3.5 mm day^{-1} in a Polish marshland on peat soils. Annual ET in these sites ranged from 292 to 372 mm over multiple years in these sites. Our higher modeled annual ET of 695 to 696 mm compared with natural wetlands was not unexpected because of the provision of fertilizer and supplemental summer irrigation for the managed cranberry crop.

We used direct and bog-specific measurements of water pumped into bogs or bog water levels to calculate surface water input to bogs, and direct measurements of water flow through water control flumes on bog outlets to calculate surface water inputs and outputs. This approach was applied by Kennedy (2015) to measure water fluxes during fall and winter cranberry floods in Massachusetts bogs. We measured water inputs and outputs that were in the same range as reported by Kennedy (2015) for Rocky Pond Bog, State Bog and one additional bog during fall 2013 and winter 2013 floods. Our findings extended this approach to quantify the water budget over an entire water year.

Our results clearly showed that the exchanges of groundwater with cranberry bogs varied widely based on the particular hydro-geographical setting occupied by any single bog. Two of our bogs (Rocky Pond and White Springs Bogs) occupied topographic lows in the landscape and were sites of net groundwater discharge. Between these two bogs, net groundwater discharge varied widely from 1,170 and 5,970 mm/yr. State Bog was a site of net groundwater recharge and occupied a location with more level topography. Net discharge of groundwater into bogs has been documented at Massachusetts cranberry bogs that lie in low topographic positions (Barbaro et al. 2013, Briggs et al. 2016). The assumption that net annual groundwater exchanges for cranberry bogs can be estimated from simple assumptions based on regional rainfall and climate is likely not correct. For example, Masterson et al. (2009) assumed that cranberry bogs in Southeast MA behaved like natural wetlands and that they were areas of net groundwater recharge during winter months but not the growing season, and had an average recharge rate of 254 mm yr^{-1} (10 in yr^{-1}). This contrasted with the wide variation we found. The estimate from Masterson et al. (2009) was based in part on a study of one MA ombrotrophic bog that lay near a watershed divide and did not have groundwater inflow (Hemond 1980).

Because water levels in cranberry bogs are manipulated, exchanges of water between bogs and groundwater vary seasonally and depend on differences in hydrologic head created by bog flooding. Kennedy (2015) found that bogs contributed net flow of water to the groundwater during flood periods when water was over the bog surface. He calculated that recharge was 50 to 170 mm during harvest floods and 290 to 590 mm during the longer winter floods. However, these estimates were only for the times bogs were flooded and did not represent net annual water movement because water is flowing from the groundwater into bogs at other times. At Rocky Pond and White Springs Bogs we found that net annual water movement was from the groundwater into the bog during the majority of the year when the bog was not flooded. In contrast, at State Bog, net water movement was into the groundwater. Because net discharge occurred at other times of year, the net annual groundwater recharge that we calculated of 175 mm was lower than estimated by Kennedy (2015) based solely on times the bogs were flooded.

Our estimates of the total amount of water used for irrigation for spring frost protection and summer supplemental moisture of 708 to 847 mm were within the wide range of 154 to 921 mm yr^{-1} measured in MA cranberry bogs in 2014 and 2015 (Kennedy et al. 2017). Our values likely fell in the higher end of this range because of unusually low rain during the growing season and spring cold periods in 2016 required additional irrigation. Despite precipitation during the 2016 water year that was near the long-term average, precipitation during the growing season in June, July and August 2016 of 60 mm was much lower than the 1960 to 2014 average of 278 mm.

Estimates of bog water budgets could have been improved by direct measurement of irrigation water inputs to White Springs Bog. We also used precipitation data from one centrally-located weather station, but this could have missed some variability in rainfall over each bog particularly during convective summer storms.

Temporal nutrient dynamics

In harvest floods, the pattern of low dissolved N concentrations in inflowing floodwater and increasing concentrations of NO_3^- and NH_4^+ during the middle or latter stages of flood releases were consistent with the pattern measured by Kennedy et al. (2015) for State Bog. This pattern was most likely explained by interaction of floodwater with the bog bed. Export of low-N surface waters occurred during the early portion of flood release but a transition to export of higher-N pre-event soil waters from the bog bed occurred during the latter stages of flood release when water levels fell below the level of the bog platform (Kennedy et al. 2015). Our results indicated that this pattern occurred for both NH_4^+ and NO_3^-, but the peak occurred later in the flood release for DON than for DIN.

High PO_4^{3-} and TP concentrations during the first half of flood releases were consistent with PO_4^{3-} releases from cranberry bog soils after the initiation of flooding when soils became anoxic (DeMoranville et al. 2009). The release of P from flooded anoxic sediments is an important mechanism for P release to surface waters in a variety of wetlands and agricultural soils (Patrick and Mahapatra 1968, Shenker et al. 2004, Kinsman-Costello et al. 2014). This phenomenon may have contributed to the 15 to 31% of total annual P export that occurred during the harvest flood. However, in all bogs, a greater percentage of P released in harvest floods was organic P compared with PO_4^{3-} (although PO_4^{3-} and organic P were released in nearly equal amounts from White Springs Bog). Because this organic P contains both dissolved and particulate P, high organic P export during the end of the first half of the flood release may have been caused by movement of particulate P during mid flood when water velocities were highest.

The lower and less dynamic concentrations of dissolved and particulate N during winter floods compared with harvest floods likely occurred because of lower temperatures during the months of January to early April when winter floods occurred and because winter floods are specifically applied during the coldest periods within those months (DeMoranville 2008). Greater variation in groundwater inputs during the winter, when groundwater recharge typically occurs (Masterson et al. 2009), may also have contributed to less predictable responses of solute concentrations in winter floods compared with harvest floods.

Patterns of solute concentration response during storm hydrographs can provide important information on solute sources within watersheds (Hill et al. 2009, McHale et al. 2002, Inamdar et al. 2004). Recent evidence from cranberry bogs in southeastern MA suggests that export of dissolved N, particularly export of DON, can be very high after rainstorms that occur during the growing season (DeMoranville et al. 2016, Alverson et al. in prep). Kennedy et al. (2017) estimated output of about 9 kg N ha^{-1} during summer from one bog that included measurements during a 41 mm rainfall. Our finding of very little change in dissolved N or P concentrations following growing season rainstorms differed from that finding. Two factors may be responsible for this difference. First, rainstorms we captured were relatively small and spanned only 7 to 35 mm across all bogs and the 2016 growing season had abnormally low rainfall. Total rainfall in June, July and August 2016 was 60 mm and less than 22% of the long-term mean rainfall of 278 mm measured in those months from 1960 to 2014 at the closest monitoring station in Lakeville, MA (MA EOEEA 2017b). Second, the bog studied by Alverson et al. was a newly-renovated upland bog with tile drains and 3.1 kg N ha^{-1} out of approximately 9 kg N ha^{-1} total summer export was through the tile drains. It is possible that solute dynamics following rainstorms differ between upland bogs and the more standard wetland bogs that we studied. Studies of more bog types would be necessary to determine if this were the case.

Nutrient measurements and estimates of annual flux estimates

This study contains the most detailed measurements yet made of surface water exchanges of N and P and included both periods of cranberry bog floodwater management and non-flood periods over a complete water year. However, there were two potential sources of uncertainty in N and P fluxes and partitioning total N and P into different dissolved and particulate forms. One source of uncertainty was that we used concentrations measured by composite sampling or grab sampling to fill gaps during which we had no sampling because freezing temperatures made composite sampling with automatic samplers unfeasible because of freezing of pumps and intake lines (primarily periods during January to March 2016 that were not during winter floods). Because concentrations in outflowing water at these times varied very little, this introduced only modest uncertainty into our flux estimates. Another source of uncertainty was the fact that composite sampling with automatic samplers required addition of sulfuric acid as a preservative in the sample bottles. This did not alter the distribution of N forms but overestimated PO_4^{3-} relative to unpreserved samples, likely because of oxidation of organic dissolved and particulate P to PO_4^{3-} during the time that samples remained in the automatic samplers after collection. Estimates of total P were not affected by the preservation. Because we did not include the PO_4^{3-} and organic P contained in composite samples in our estimates of annual PO_4^{3-} and organic P export, our estimates of annual export of P as PO_4^{3-} and organic P are underestimates. The estimate of total P, however, was unaffected because total P was similar in preserved and unpreserved samples.

A potential uncertainty in this study was the estimate of the amount of N or P that entered or left the bog in groundwater. For Rocky Pond and White Springs Bogs, which had net groundwater inputs, we used the median concentration of dissolved N or P sampled over more than one year on upgradient groundwater to estimate the flux of N and P from groundwater into the bogs. We assumed that the product of water flow and the concentrations measured in upgradient wells was the mass of N and P that entered the bog annually. We used the annual average concentrations of solutes in groundwater because groundwater that discharges to the bog arrives from a range of locations in the watershed and because we observed little seasonal variation in groundwater solute concentrations. In Rocky Pond Bog, because incoming groundwater flow was large, small differences in concentration could potentially change the estimate of incoming N flux of 9.1 kg N y^{-1}. However, upgradient groundwater NH_4^+ and NO_3^- concentrations were low and relatively similar among wells and over time. In State Bog, which had net groundwater output, we assumed the median concentrations measured in downgradient wells represented the N and P that moved from the bog into groundwater. While it might be possible to improve the estimate of the total flux of N and P by sampling a larger number of up- or downgradient groundwater wells, it is possible that groundwater could move preferentially into or out of individual bogs within spatially distinct flow pathways. Such pathways, such as preferential flow pipes that move water upward and into bogs through underlying peat have been identified in cranberry bogs (Biggs et al. 2010). Determining these pathways precisely, however, would take much more detailed examination of groundwater flows in and around individual bogs.

Export of N and P from cranberry bogs following rainstorms during the growing season has been identified as potentially important in southeastern Massachusetts cranberry bogs (Alverson et al. in prep). This is currently very poorly quantified and could be an important component of annual fluxes from cranberry bogs. Because precipitation is projected to become more variable in the Northeast U.S. under future climate (Horton et al. 2014), nutrient releases following heavy rains during the growing season could become more important in the future, and managing these releases could play a greater role in future watershed nutrient management. We measured very low export following growing season rainstorms. However, the study period of June, July and August 2016 was unusually dry and experienced precipitation that was less than 22% of the long-term average. Our finding of low export during growing season storms in this unusual period does not indicate that such export could not or would not occur in years with greater rainfall.

Comparisons with previous measurements

The range of fluvial fluxes of 1.5 to 2.1 kg N ha^{-1} we measured during harvest floods was a narrower range than in previous studies (Table 15). The range of fluvial fluxes of -0.3 to 2.3 kg N ha^{-1} we measured during winter floods was slightly wider but generally similar to those measured by the Town of Carver (2015) but narrower than the -6.9 to 3.6 kg N ha^{-1} measured by DeMoranville and Howes (2005). Our estimate of net export of 1.55 kg N ha^{-1} from State Bog during the fall 2015 flood was slightly higher but in the same range as the 0.8 kg N ha^{-1} measured by Kennedy et al. (2015) during the fall 2012 at State Bog.

The range of fluvial fluxes of 0.2 to 1.5 kg P ha^{-1} we measured in harvest floods fell in a narrower range than reported by the Town of Carver et al. (2015) or DeMoranville and Howes (2005) (Table 15). The range of fluvial fluxes of 0 to 0.5 kg P ha^{-1} that we measured in winter floods was slightly lower than measured by DeMoranville and Howes (2005) or Town of Carver et al. 2015) (Table 15).

The total annual exports of N (-2.8 to 12.4 kg N ha^{-1}) and P (2.2 to 4.5 kg P ha^{-1}) measured in the three bogs in this study were lower than the exports of 25.8 kg N ha^{-1} and 11.1 kg P ha^{-1} measured from a flow-through bog by Howes and Teal (1995) (Table 15). We measured lower annual export of N compared with the export of 16.3 to 9.3 kg N ha^{-1} measured from an upland bog by Kennedy et al. (2018) but similar annual export of P compared with the 3.3 to 1.3 kg P ha^{-1} measured in that study (Table 15).

Implications for coastal watersheds and potential for nutrient reduction by management

Nitrogen. Bogs varied from a net source of exchange with surface water of 12.7 kg N ha^{-1} in Rocky Pond to a net sink of 2.0 kg N ha^{-1} in White Springs Bog. This variation occurred even though the amount of N fertilizer applied and the amount and timing of water applied for crop management were generally similar across all bogs. This variability of net N exchange likely arose from the geographical setting in which the bogs occurred. Rocky Pond Bog received a high volume of groundwater from the surrounding watershed. Because a large proportion (77%) of the N export from Rocky Pond Bog occurred in non-flood baseflows during the growing season when dissolved N concentrations in surface waters were high, the large amount of water that exited Rocky Pond Bog in growing season non-flood baseflow led to high annual N export. In contrast, State Bog, which had very low growing season non-flood outflow of water, exported far less N (although the proportion of total N exported as non-growing season flow was high).

Net groundwater exchange alone did not determine the pattern of N export and the concentrations of N in surface water also played an important role. White Springs Bog also received groundwater inputs and had significant growing season non-flood baseflow, but had lower N export than N input because N concentrations in outflowing surface water were low. These concentrations are likely determined by interactions of surface waters with soils of the bog and particularly bog ditches with which inflowing groundwater has prolonged contact during the growing season when exports in non-flood baseflow occur. Based on total net N exchanges, despite receiving very similar amounts of N fertilizer, very similar water management, and similar N removal in harvested biomass, White Springs and State Bogs had net total N retention and Rocky Pond Bog had net N loss primarily because surface N output in non-flood surface water from Rocky Pond Bog was high.

The variation in both the magnitude and direction of net N exchanges among bogs makes it difficult to determine a "typical" N exchange for cranberry bogs in Massachusetts coastal watersheds. However, the combination of detailed hydrological and chemical measurements from which our annual estimates were derived provides increased confidence in the magnitude of these exchanges. The consistency of the exchanges in harvest and winter floods that we measured compared with those measured by DeMoranville and Howes (2005) and Town of Carver (2015) indicate that the net annual N exchanges that we measured were likely typical or slightly lower than the annual N exchanges that occurred in the bogs examined in those studies. Our results and those of DeMoranville and Howes (2005) and Town of Carver (2015) applied to bogs in which bog platforms were physically separated from surface waters by levees and water control structures. The lower estimates of annual N fluxes that we measured compared with Howes and Teal (1995) for a flow-through bog not separated from surface waters by levees and water control structures, were consistent with the greater physical separation from surface waters of the bogs we examined. The bogs examined all followed best management practices for water and fertilizer management as described by the University of Massachusetts Cranberry Experiment Station (Ghantous et al. 2017). It is possible that other bogs that do not adhere to best management practices would be different.

Nitrogen released from cranberry bogs to streams and rivers in coastal watersheds is potentially important because delivery of excess N to estuaries causes a series of cascading changes associated with eutrophication that include algae production, loss of submersed aquatic vegetation, increased occurrence of anoxia, and loss of fish and shellfish (Valiela et al. 1992, Deegan et al. 2002, Howarth and Marino 2006, Bricker et al. 2007). The role of cranberry bogs, compared with other potential sources, in delivering N to the estuary of any particular watershed will depend not only on the N released per unit bog area that we measured, but also the total area of bogs in watersheds, the form of N released to surface waters, and the extent to which N released to surface waters is either conveyed downstream in streams and rivers or lost within river channel networks. Our findings indicate that on a per area basis, net contributions of N to watersheds are relatively modest compared with other N sources. For example, based on a watershed N loading model (Valiela et al. 1997) widely applied in southeastern Massachusetts, one single-family home on a septic system with an average occupancy of 1.8 people would generate 8.6 kg N yr^{-1} (based on the per capita N in waste of 4.8 kg N $person^{-1}$ yr^{-1}). At a density of 2.5 houses ha^{-1} (1 house ac^{-1}), a residential area would release approximately 21.5 kg N ha^{-1} to the watershed, compared with 12.7 kg N ha^{-1} released from the bog (Rocky Pond) that had the highest annual fluvial N export.

This direct comparison of N released into the watershed does not correspond directly with the effect of N when it reaches receiving waters. This is because N is then subjected to attenuation in the flowpath between the water body and the entry point of N to the watershed. For example, N entering in septic tanks is generally subjected to attenuation of 0.60 in the septic tank and leach field, 0.39 in the soil vadose (unsaturated) zone and 0.65 in the aquifer (Valiela et al. 1997). Thus, while the total N released within the watershed of one hectare of cranberry bogs is less than the N generated by one hectare of residential area on-site wastewater treatment, because cranberry bogs release N directly to surface waters where cumulative N attenuation is likely to be lower, the proportional amount of N release delivered to the estuary could potentially be greater. This study did not consider the effect of attenuation within freshwater stream networks as an influence on the ultimate effect of N released from cranberry bogs. The attenuation of N within river networks has been examined in other locations but is still relatively poorly quantified. Some studies indicate that small streams and rivers strongly influence N export from river networks because contact between flowing water and the stream bottom or hyporheic zone, where most N removal by plant uptake or denitrification occur, is highest in small streams (Alexander et al. 2000, Peterson et al. 2001, Bernot and Dodds 2005). Other studies suggest that significant N removal occurs in larger river channels because a large amount of basin runoff enters larger rivers directly (Seitzinger et. al 2002a). Wollheim et al. (2006) used a river network model to estimate that 27 and 72% of aquatic N inputs were removed within first to fourth order streams in the Ipswich River Basin, a 400-km^2 watershed in coastal northeastern Massachusetts that is roughly similar in size and topography to the Wareham and Weweantic Rivers. Assuming this same rate of removal with the stream network, the amount of N delivered to estuary from Rocky Pond Bog would be 3.6 to 9.3 kg (based on the measured fluvial N output from Rocky Pond Bog of 12.7 kg N ha^{-1}).

One additional potentially important finding was that a large majority of total dissolved N exported from all bogs during harvest floods (92 to 96%) was as DON. The proportion of total dissolved N exported as DON from all bogs during winter floods was also high (72 to 86%). Export as DON during the non-flood periods was also important but proportionally lower (38 to 49%). Because the amount of dissolved N moving in non-flood flows was high, a total of 45 to 66% of all measured dissolved N exported in surface waters was as DON. Because DON is generally less bioavailable to aquatic plants and bacteria than DIN (Seitzinger et al. 2002b), this suggests that about half of the dissolved N exported from cranberry bogs to surface waters during harvest floods will be less biologically available than the NO_3^- that is typically delivered to surface waters from portions of southeastern MA watersheds with high suburban or densities of residential development with on-site wastewater treatment (Valiela et al. 1997).

Our findings also suggest several potential approaches to managing overall N releases from cranberry bogs. Kennedy et al. (2015) found that 58% of total N released during the flood event occurred during the last 22% of the time period during which floodwater was released. This indicated that there might be potential to treat this late-flood, high-N water using techniques such as in-line bioreactors (Blowes et al. 1994, Jaynes et al. 2004, Schipper et al. 2010). Our fine-scale sampling of floodwater releases also showed that both NO_3^- and NH_4^+ concentrations generally increased during the latter half of flood releases and that increase was substantial. However, because the amount of water moving during the latter portion of the flood release was relatively low, these concentration changes did not have a large effect on total N release during the entirety of the flood. In contrast, most N was released to surface waters during non-flood periods. This indicated that additional water management specifically aimed at N removal from the small but steady outflow of surface water that occurs from most bogs during non-flood periods could be beneficial. Such management might include additional storage time in ponds or increased naturalization of stream channels to enhance N uptake and potentially denitrification, has been shown to occur in some managed streams (Groffman et al. 2004). In contrast, releases to groundwater were small. These would be harder to manage because they occur during flooding that is required for harvest and winter frost protection and the return on any new investments in managing would likely be relatively minor.

Phosphorus. All bogs were net sources of P to surface waters. Because this P was released directly to surface waters and because both PO_4^{3-} and organic P concentrations in surface and groundwater were low, this released P could have important effects on downstream ecosystems. This would be particularly important for freshwater ponds that are downstream of cranberry bogs because pond algae would be more likely to be P limited. Our fine-scale sampling of flood releases showed that the concentrations of the most available form of P (PO_4^{3-}) were high during the initial stages of flood release when water flow was high. Additional water management specifically targeted at removing P from the large volume of outflowing floodwater would likely be required to lessen this P release. This poses a somewhat different management issue than for N because it would require treating floodwater releases compared with treating the smaller but steady volume of non-flood water releases that would be most beneficial for decreasing N contributions to watersheds.

This study of three cranberry bogs substantially expands the available information on nutrient exchanges between cranberry bogs and watersheds. It also provides information on N and P movement during different phases of cranberry bog water management across an annual cycle. The N balances reported in this study varied substantially but were generally lower and varied less than those reported in previous studies. The P balances reported were also lower than in previous studies and varied relatively little. While the bogs we studied did not represent the entire range of bog types and hydro-geographical settings in which bogs occur in southeastern Massachusetts, these results should provide estimates of nutrient exchanges between cranberry bogs and coastal watersheds.

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References

Alexander, R. B., R. A. Smith and G. E. Schwarz. 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature 403:758–761.

Bland, W. L., J. T. Loew and J. M. Norman. 1996. Evaporation from cranberry. Agricultural and Forest Meteorology 81:1-12.

Bernot, M. and W. K. Dodds. 2005. Nitrogen retention, removal, and saturation in lotic ecosystems. Ecosystems 8:442–453.

Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks and J. Woerner. 2007. Effects of nutrient enrichment in the nation's estuaries: a decade of change. NOAA Coastal Ocean Program, Decision Analysis Series No. 26, National Centers for Coastal Ocean Science. Silver Spring, MD.

Briggs, M.A., M. N. Gooseff, B. J. Peterson, K. Morkeski, W. M. Wollheim and C. S. Hopkinson. 2010. Surface and hyporheic transient storage dynamics throughout a coastal stream network. Water Resources Research. W06516, doi:10.1029/2009WR008222.

Bowen, J. L. and I. Valiela. 2001. Historical changes in atmospheric nitrogen deposition to Cape Cod, Massachusetts, USA. Atmospheric Environment 35:1039-1051.

Buzzards Bay Coalition. 2016. Inner Weweantic River. http://www.savebuzzardsbay.org/bay-health/waterway/weweantic-river/inner-weweantic-river/. Accessed June 15, 2016.

BBNEP (Buzzards Bay National Estuaries Project). 2016. Information about cranberry bogs and the environment. http://www.buzzardsbay.org/craninfo.htm. Accessed September 2016.

Cannon, D. and H. A. Sandler. 2014. Distribution of MA cranberry varieties—2014. Cranberry Station Research Reports and Surveys. Paper 19. http://scholarworks.umass.edu/cranberry_research_repts/19.

Caraco, N., A. Tamse, O. Boutros and I. Valiela. 1987. Nutrient limitation of phytoplankton growth in brackish coastal ponds. Canadian Journal of Fisheries and Aquatic Sciences 44: 473-476.

Davenport, J., C. DeMoranville, J. Hart and T. Roper. 2000. Nitrogen for bearing cranberries in North America. EM 8741. Oregon State University Extension Service, Corvallis, OR. 18 pp.

Deegan, L. A., A. Wright, S. G. Ayvazian, J. T. Finn, H. Golden, R. R. Merson and J. Harrison. 2002. Nitrogen loading alters seagrass ecosystem structure and support of higher trophic levels. Aquatic Conservation: Marine and Freshwater Ecosystems 12:193-212.

DeMoranille, C. J. 2008. Flood management. Pages 66-71 in C. J. DeMoranville and H. A. Sandler, editors, *Cranberry Production: A Guide for Massachusetts*. University of Massachusetts Publication CP-08, University of Massachusetts Amherst Cranberry Station, East Wareham, MA.

DeMoranville, C. and B. Howes. 2005. Phosphorus dynamics in cranberry production systems: Developing the information required for the TMDL process for 303D water bodies receiving cranberry bog discharge. Final Project Report to Massachusetts Department of Environmental Protection.

DeMoranville, C., P. Jeranyama, C. Kennedy, H. Sandler, E. S. Rojas and F. Caruso. 2016. Use of tile drainage in Massachusetts cranberry production. University of Massachusetts Amherst Cranberry Station, Fact Sheet. http://ag.umass.edu/sites/ag.umass.edu/files/fact-sheets/pdf/use_of_tile_drainage_in_massachusetts_cranberry_2016.pdf. Accessed Jan. 2017.

Drexler, J. Z., R. L. Snyder, D. Spano and K. T. P. U. 2004. A review of models and micrometeorological methods used to estimate wetland evapotranspiration. Hydrological Processes 18:2071-2101.

Eck, P. 1990. *The American Cranberry*. Rutgers University Press, New Brunswick, NJ. 420 pp.

Elser, J. J., M. E. S. Bracken, E.E. Lleland, D. S. Gruner, W. S. Harpole, H. Hildenbrand, J. T. Ngai, W. E. Seabloom, J. B. Shurin and J. E. Smith. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology Letters 10: 1135-1142.

Ghantous, K., M. Sylvia and D. Gauvin (Eds) 2017. *Cranberry Chart Book Management Guide for Massachusetts*. University of Massachusetts Cranberry Experiment Station, East Wareham, MA. Available at http://ag.umass.edu/sites/ag.umass.edu/files/management-guides/2017_chart_book_final.pdf

Gore, J. A. 2007. Discharge measurements and streamflow analysis. Pages 51-78 in *Methods in Stream Ecology*, F. R. Hauer and G. A. Lamberti (Eds). Academic Press, Burlington, MA.

Groffman, P. M., N. L. Law, K. T. Belt, L. E. Band and G. T. Fisher. 2004. Nitrogen fluxes and retention in urban watershed ecosystems. Ecosystems 7:393-403.

Hart, J. M., B. C. Strik, C. DeMoranville, J. R. Davenport and T. Roper. 2015. Cranberries: A nutrient management guide for south coastal Oregon. EM 8632. Oregon State University Extension Service, Corvallis, OR. 51 pp.

Hemond, H. F. 1980. Biogeochemistry of Thoreau's Bog, Concord, Massachusetts. Ecological Monographs 50:507-526.

Hill, A. R., W. A. Kem, J. A. Buttle and D. Goodyear. 1999. Nitrogen chemistry of subsurface storm runoff on forested Canadian Shield hillslopes. Water Resources Research 35, 811–821.

Horton, R., G. Yohe, W. Easterling, R. Kates, M. Ruth, E. Sussman, A. Whelchel, D. Wolfe, and F. Lipschultz. 2014. Chapter 16: Northeast. Pages 371 to 395 in Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, T. C. Richmond, and G. W. Yohe (Eds), U.S. Global Change Research Program, 371-395. doi:10.7930/J0SF2T3P.

Howarth, R. W. and R. Marino. 2006. Nitrogen as the limiting nutrient for eutrophication of coastal marine ecosystems: evolving views over three decades. Limnology and Oceanography 51:364-376.

Howes, B. L. and J. M. Teal. 1995. Nutrient balance of a Massachusetts cranberry bog and relationships to coastal eutrophication. Environmental Science and Technology 29: 960-974.

Inamdar, S. P., S. Christopher and M. J. Mitchell. 2004. Export mechanisms for dissolved organic carbon and nitrate during summer storm events in a glaciated forested catchment in New York, USA, Hydrological Processes 18, 2651– 2661.

Jakuba, R, L. Scott, C. Neill, C. and C. DeMoranville. 2015. Quality Assurance Project Plan for Reducing Nutrient Losses from Cranberry Bogs, Submitted to EPA Region 1, September 9, 2015.

Jaynes, D. B., T. C. Kaspar, T. B. Moorman andT. B. Parkin 209. In situ bioreactors and deep drain-pipe installation to reduce nitrate losses in artificially drained fields. Journal of Environmental Quality 37: 429-436.

Kennedy, C. D. 2015. Hydrologic and nutrient response of groundwater to flooding of cranberry farms in southeastern Massachusetts, USA. Journal of Hydrology 525:441–449.

Kennedy, C. D., A. R. Buda, P. J. A. Kleinman and C. J. DeMoranville. 2015. Chemical and isotopic tracers illustrate pathways of nitrogen loss in cranberry floodwaters. Journal of Environmental Quality 44:1326-1332.

Kennedy, C. D., N. Alverson, P. Jeranyana and C. DeMoranville. 2018. Seasonal dynamics of water and nutrient fluxes in an agricultural peatland. Hydrological Processes. doi: 10.1002/hyp.11436

Kennedy, C. D., P. Jeranyama and N. Alverson. 2017. Agricultural water management for commercial production of cranberries. Canadian Journal of Soil Science 97:38-45.

Kim, J. and S. B. Verma. 1996. Surface exchange of water vapour between an open *Sphagnum* fen and the atmosphere. Boundary Layer Meteorology 79:243-264.

Kniffin, M., C. Neill, R. M. McHorney and G. Gregory. 2009. Nutrient limitation of periphyton and phytoplankton in Cape Cod coastal plain ponds. Northeastern Naturalist 16:395-408.

Kroeger, K.D., M. L. Cole and I. Valiela. 2006. Groundwater-transported dissolved organic nitrogen from coastal watersheds. Limnology and Oceanography 51:2248-2261.

Lafleur, P. M., R. A. Hember, S. W. Admiral and N. T. Roulet. 2005. Annual and seasonal variability in evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada. Hydrological Processes 19:3533-3550.

MA EOEEA (Massachusetts Executive Office of Energy and Environmental Affairs). 2017a. Agricultural resource facts and statistics. http://www.mass.gov/eea/agencies/agr/statistics/. Accessed January 2017.

MA EOEEA (Massachusetts Executive Office of Energy and Environmental Affairs). 2017b. Massachusetts precipitation data. http://www.mass.gov/eea/agencies/dcr/water-res-protection/water-data-tracking/rainfall-program.html. Accessed January 2017.

MA Estuaries Project (Massachusetts Estuaries Project). 2017. Completed nutrient management reports for 45 estuaries. http://www.oceanscience.net/estuaries/. Accessed January 2017.

MA GIS. 2014. MassDEP 204 Intergrated list of waters (305(b)/303(d)). MA Executive Office of Administration and Finance http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/wbs2014.html. Accessed January 2017.

Mahowald, N., T. D. Jickells, A. R. Baker, P. Artaxo, C. R. Benitez-Nelson, G. Bergametti, T. C. Bond, Y. Chen, D. D. Chen, B. Herut, N. Kubilay, R. Losno, C. Luo, W. Maenhaut, K. A. McGee, G. S. Okiin, R. L. Siefert and S. Tsukuda. 2008. Global distribution of atmospheric sources, concentrations and deposition rates and anthropogenic impacts. Global Biogoechemical Cycles 10.1029/2008GB003240.

Masterson, J. P., C. S. Carlson and D. A. Walter. 2009. Hydrogeology and simulation of groundwater flow in the Plymouth-Carver-Kingston_Duxbury Aquifer System, Southeastern Massachusetts. US Gelogical Survey Scientific Investigations Report 2009-5063. 110 pp.

McHale, M. R., J. J. McDonnell, M. J. Mitchell and C. P. Cirmo. 2002. A field-based study of soil water and groundwater nitrate release in an Adirondack forested watershed, Water Resources Research 38, 1031, doi:10.1029/2000WR000102.

Mitsch, W. J. and J. G. Gosselink. 2015. *Wetlands*. 5th edition, John Wiley, Hoboken, NJ. 456 pp.

Nixon, S.W. 1995. Coastal marine eutrophication: A definition, social causes, and future concerns. Ophelia 41:199–219.

Oglesby, R. T. 1977. Phytoplankton summer standing crop and annual productivity as functions of phosphorus loading and various physical factors. Journal of the Fisheries Research Board of Canada 34:255-2270.

Paerl, H. W., J. T. Scott, M. J. McCarthy, S. E. Newell, W. S. Gardner, K. E. Havens, K. K. Hoffman, S. W. Wilhelm and W. A. Wurtbaugh. 2016. It takes two to tango: When and where dual nutrient (N & P) reductions are needed to protect lakes and downstream ecosystems. Environmental Science and Tehcnology 50:10,805-10,813.

Patrick, W. H., Jr. and I. C. Mahapatra. 1968. Transformation and availability to rice of nitrogen and phosphorus in waterlogged soils. Advances in Agronomy 20:323-359.

Peterson, B. J., L. Deegan, J. Helfrich, J. E. Hobbie, M. Hullar, B. Moller, T. E. Ford, A. Hershey, A. Hiltner, G. Hipphut, M. A. Lock, D. M. Fiebig, V. McKinley, M. C. Miller, J. R.

Vestal, R. Ventullo and G. Volk. 1993. Biological responses of a tundra river to fertilization. Ecology 74:653-672.

Peterson B. J, W. M. Wolheim, P. J. Mulholland, J. R. Webster, J. L. Meyer, J. L. Tank, E. Martí, W. B. Bowden, H. M. Valett, A. E. Hershey, W. H. McDowell, W. K. Dodds, S. K. Hamilton, S. V. Gregory and D. D. Morrall. 2001. Control of nitrogen export from watersheds by headwater streams. Science 292:86-90.

Priestley, C. H. B. and R. J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100: 81–82.

Roper, T., J. Davenport, C. DeMoranville, S. Marchand and A. Poole. 2004. Phosphorus for bearing cranberries in North America. Cranberry Station Fact Sheet. Paper 11. University of Massachusetts Cranberry Station, Wareham, MA. 11 pp. Available at http://scholarworks.umass.edu/cranberry_factsheets/?utm_source=scholarworks.umass.edu%2Fcranberry_factsheets%2F11&utm_medium=PDF&utm_campaign=PDFCoverPages. Accessed January 2017.

Schipper, L. A., W. D. Robertson, A. J. Gold, D. B. Jaynes and S. C. Cameron. 2010. Denitrifying bioreactors—an approach for reducing nitrate loads to receiving waters. Ecological Engineering 36:1532-1543.

Seidlecki, M., W. Pawlak, K. Fortuniak and M. Zielinski. 2016. Wetland evapotranspiration: eddy covariance measurement in the Biebrza Valley, Poland. Wetlands 36:1055-1067.

Seitzinger, S. P., R. V. Styles, E. W. Boyer, R. B. Alexander, G. Billen, R. W. Howarth, B. Mayer and N. van Breemen. 2002a. Nitrogen retention in rivers: Model development and application to watersheds in the northeastern USA. Biogeochemistry 57:199–237.

Seitzinger. S. P., R. W. Sanders and R. Styles. 2002b. Bioavailability of DON from natural and anthropogenic sources to estuarine plankton. Limnology and Oceanography 47:353–366.

Thomas, J. D. (ed.) 1990. *Cranberry Harvest: A History of Cranberry Growing in Massachusetts*. Spinner Publications, New Bedford, MA. 224 pp.

Town of Carver, Buzzards Bay Coalition, Marine Biological Laboratory and University of Massachusetts Cranberry Station. 2015. Cranberry Bog Nutrient Loss Study 2011-03/604 Final report prepared for Massachusetts Department of Environmental Protection Bureau of Water Resources and U.S. Environmental Protection Agency Region 1. 58 pp.

UMass Cranberry Station. 2016. Cranberry 2016 Chart Book: Management Guide for Massachusetts. University of Massachusetts Amherst, Cranberry Station. http://ag.umass.edu/sites/ag.umass.edu/files/management-guides/chart_book_2016.pdf Accessed January 2016.

USDA (United States Department of Agriculture). 2016. Cranberry highlights. National Agricultural Statistics Service, New Jersey Field Office. http://www.nass.usda.gov/Statistics_by_State/New_Jersey/Publications/Cranberry_Statistics/CRANSUM_Final.pdf. Accessed April 2017.

Valiela, I., K. Foreman, M. LaMontagney, D. Hersh, J. Costa, P. Peckol, B. DeMeo-Andreson, C. D'Avanzo, M. Babione, C-H Sham, J. Brawley and K. Lajtha. 1992. Couplings of watersheds and coastal waters: Sources and consequences of nutrient enrichment in Waquoit

Bay, Massachusetts. Estuaries 15:443-457.

Valiela, I., J. Kremer, K. Lajtha, M. Geist, B. Seely, J. Brawley and C. H. Sham. 1997. Nitrogen loading from coastal watersheds to receiving estuaries: a new method and application. Ecological Applications 7:358-380.

Vanderleest, C. P. L. and W. Bland. 2016. Evapotranspiration from cranberry compared to the equilibrium rate. Canadian Journal of Soil Science, 10.1139/CJSS-2015-0093.

Vet, R. S. Artz, S. Carou, M. Shaw, C.-U. Ro, W. Aas, A. Baker, V. C. Bowersox, F. Dentener, C. Galy-Lacaux, a. Hou, J. J. Pienaar, R. Gillett, M. C. Forti, S. Gromov, H. Hara, T. Khodzher, N. M. Mahowald, S. Nickovic, P. S. P Rao and N. W. Reid. 2014. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. Atmospheric Environment 93:3-100.

Vollenweider, R. A., M. Munawar and P Stadelmann. 1974. A comparative review of phytoplankton and primary production in the Laurential Great Lakes. Journal of the Fisheries Research Board of Canada 31:739-762.

Wollheim, W. M., C. J. Vörösmarty, B. J. Peterson, S. P. Seitzinger and C. S. Hopkinson. 2006. Relationship between river size and nutrient removal. Geophysical Research Letters doi:10.1029/2006GL025845.

Table 1. Bog names, surface area, and locations.

Bog name	Hectares (acres)	Location	Watershed	GPS Coordinates
Rocky Pond Bog (RP)	1.70 (4.20)	Bare Hill Rd, Myles Standish State Forest, Plymouth, MA	Weweantic River	41° 53’ 10.03” N 70° 41’ 53.80” W
White Springs Bog (WS)	2.91 (7.18)	E Head Rd, off Cranberry Rd, Carver, MA	Wareham River	41° 50’ 23.23” N 70° 41’ 45.65”W
State Bog (SB)	1.17 (2.89)	Cranberry Experiment Station, Wareham, MA	Wareham River	41° 46’ 01.22” N 70° 40’ 07.19” W

Table 2. Year of renovation, and fertilizer application rates and cranberry yields for 2008 to 2014 and during 2015 and 2016.

Characteristic	Year	Rocky Pond	White Springs	State
Year renovated		2002	Not renovated	2006
N fertilizer (kg N ha^{-1})	2008-2014	42	31	44
	2015	36.8	35.6	36.8
	2016	36.2	35.6	34.7
P fertilizer (kg P ha^{-1})	2008-2014	12	9	11
	2015	11.1	6.7	11.1
	2016	10.8	6.7	4.9
Yield (bbl ac^{-1})	2008-2014	222	175	89
	2015	195	250	190
	2016	285		143
Yield (Mt ha^{-1})	2008-2014	24.7	19.5	9.9
	2015	21.7	27.8	21.2
	2016	32.0		16.1

Table 3. Dates and duration (days) of harvest floods and winter floods and dates, duration (days) and rainfall amount (mm) of growing season rainstorms during the study period. The second and third winter floods of Rocky Pond and White Springs Bogs were implemented by installing boards in the outlet water control structure and allowing water to fill bog ditches. For floods, dates reflect dates water control boards were in place.

Flood		Rocky Pond	White Springs	State
Harvest 2015	Start date	17 Oct	13 Oct	30 Sep
	End date	1 Nov	27 Oct	7 Oct
	Duration	14	14	7
Winter 2016 (1st)	Start date	4 Jan	14 Jan	4 Jan
	End date	21 Jan	1 Feb	28 Jan
	Duration	17	17	24
Winter 2016 (2nd)	Start date	11 Feb	22 Feb	
	End date	15 Mar	25 Mar	
	Duration	33	32	
Winter 2016 (3nd)	Start date	4 Apr		
	End date	13Apr		
	Duration	7		
Growing season event 1	Start date	7 Apr	7 Apr	7Apr
	End date	8 Apr	8 Apr	7 Apr
	Rainfall	17	22	28
	Duration	1	1	1
Growing season event 2	Start date	17 Jul	10 Aug	30 May
	End date	18 Jul	12 Aug	31 May
	Rainfall	9	8	35
	Duration	1	2	1
Growing season event 3	Start date	10 Aug		5 Jul
	End date	11 Aug		6 Jul
	Rainfall	7		18
	Duration	1		1

Table 4. Water balance input and output components and methods used to develop cranberry bog annual water budgets.

Direction	Component	Method
Input	Precipitation	Measured directly at weather station at Cranberry Station.
	Surface water moved during harvest and winter floods	Measured directly from pump records for Rocky Pond and State Bogs. Estimated from change in water volume on bog during flooding for White Springs Bog.
	Surface water for irrigation for frost protection, supplemental summer moisture and subsurface summer moisture	Measured directly from pump records for Rocky Pond and State Bogs. Estimated for White Springs Bog based on requirement at nearby Rocky Pond Bog.
	Groundwater	Estimated from sum of total annual outputs minus total annual inputs.
Output	Evapotranspiration	Modeled from daily temperature, humidity and solar radiation.
	Surface water	Measured directly from stage at outlet flume.

Table 5. Number of samples of different water sample types collected in this project. Composite samples were composites of daily samples for four consecutive days.

Sample type	Rocky Pond	White Springs	State	Total
Surface water during floods	152	159	102	413
Composite surface water during non-flood periods	44	47	46	137
Groundwater	71	43	60	174
Surface water following growing season rainstorms	65	66	82	213
Grab samples of irrigation source waters	2	3	1	6

Table 6. Components of the annual hydrologic balance for three cranberry bogs.

Direction	Source	Source component	Rocky Pond	White Springs	State
			——	mm y^{-1}	——
Inputs	Precipitation		1,164	1,164	1,184
	Surface water	Harvest flood	646	391	478
		Winter flood	847	239	603
		Irrigation—frost	606	606	428
		Irrigation—summer	102	102	282
		Irrigation—subsurface	0	0	145
		Subtotal surface water	2,201	1,338	1,936
	Ground water		5,970	1,170	0
Outputs	Evapotranspiration		696	696	695
	Surface water	Harvest flood	693	523	218
		Winter flood	1,443	383	285
		Non-flood period baseflow	6,446	1,934	1,684
		Growing season storms	57	136	86
		Subtotal surface water	8,639	2,976	2,273
	Ground water		0	0	152

Table 7. Percent of the annual hydrologic budget comprised by different water budget components.

Direction	Source	Component	Rocky Pond	White Springs	State
Inputs	Precipitation		12	32	38
	Surface water	Harvest flood	7	11	15
		Winter flood	9	7	19
		Irrigation	8	19	28
	Ground water (net)		64	32	0
Outputs	Evapotranspiration		7	19	22
	Surface water	Harvest flood	7	14	7
		Winter flood	15	10	9
		Non-flood baseflow	69	53	54
		Growing season storms	1	4	3
	Groundwater (net)		0	0	6

Table 8. Median concentrations of NO_3^-, NH_4^+ and DON in groundwater measured in wells upgradient and downgradient of bogs. BMDL=below minimum detection limit.

		NO_3^- (mg L^{-1})			NH_4^+ (mg L^{-1})			DON (mg L^{-1})		
Bog	n	Median	Min	Max	Median	Min	Max	Median	Min	Max
Rocky Pond										
Upgradient	41	0.01	BMDL	0.90	0.01	BMDL	0.72	0.07	BMDL	0.69
Downgradient	30	0.01	BMDL	1.50	0.04	BMDL	0.38	0.10	BMDL	1.65
White Springs										
Upgradient	23	BMDL	BMDL	BMDL	0.01	BMDL	0.04	0.03	BMDL	0.10
Downgradient	20	0.03	BMDL	2.45	0.09	BMDL	0.37	0.16	0.05	0.71
State										
Upgradient	29	0.44	BMDL	1.57	0.02	BMDL	8.32	0.12	BMDL	0.90
Downgradient	31	0.20	BMDL	7.14	0.02	BMDL	8.43	0.13	BMDL	7.27

Table 9. Median concentrations of PO_4^{3-} and organic P in groundwater measured in wells upgradient and downgradient of bogs. BMDL=below minimum detection limit.

		PO_4^{3-} (mg L^{-1})			Organic P (mg L^{-1})		
Bog	n	Median	Min	Max	Median	Min	Max
Rocky Pond							
Upgradient	41	BMDL	BMDL	0.344	0.014	BMDL	0.064
Downgradient	30	BMDL	BMDL	0.263	0.016	BMDL	0.400
White Springs							
Upgradient	23	BMDL	BMDL	0.010	0.007	BMDL	0.035
Downgradient	20	BMDL	BMDL	0.052	0.017	BMDL	0.083
State							
Upgradient	29	BMDL	BMDL	0.177	0.037	BMDL	0.189
Downgradient	31	BMDL	BMDL	0.378	0.039	BMDL	0.697

Table 10. Annual N and P inputs and outputs in different flow pathways for Rocky Pond Bog. Values are kg N ha^{-1}y^{-1} or kg P ha^{-1}y^{-1} Fluvial fluxes include N and P moving in precipitation, surface and groundwater. Total fluxes include inputs in fertilizer and output in harvested berries and leaves. Positive net fluxes indicate output to the watershed, negative net fluxes indicate uptake by the watershed.

Inputs		NH_4^+	NO_3^-	DON	PON	Total N	PO_4^{3-}	Organic P	Total P
Precipitation		1.08	5.02	2.78	-	8.88	0	0	0
Surface water	Harvest flood	0.05	0.01	2.68	0.97	3.71	0.06	0.21	0.27
	Winter flood	0.02	0.05	0.62	0.38	1.07	0.02	0.07	0.09
	Irrigation—frost	0.06	0	1.09	0.40	1.55	0.06	0.12	0.18
	Irrigation—summer	0.01	0	0.18	0.14	0.33	0.01	0.02	0.03
	Irrigation—subsurface	-	-	-	-	-	-	-	-
Groundwater		1.01	1.01	7.10	0	9.12	0	1.42	1.42
Total fluvial input		2.23	6.09	14.45	1.89	24.66	0.15	1.84	1.99
Fertilizer		36.20	-	-	-	36.20	10.80	-	10.80
Total input		38.43	6.09	14.45	1.89	60.86	10.95	1.84	12.79
Outputs									
Surface water	Harvest flood	0.15	0.03	2.08	2.91	5.17	0.24	1.05	1.29
	Winter flood	0.36	0.15	1.28	1.60	3.39	0.10	0.48	0.58
	Non-flood baseflow	7.68	6.03	8.43	6.55	28.69	-	-	2.28
	Growing season storms	0.01	0.01	0.03	0.03	0.08	0	0	0
Groundwater		-	-	-	-	-	-	-	-
Total fluvial output		8.20	6.22	11.82	11.09	37.33	0.34	1.53	4.15
Harvest						29.75			4.40
Total output		8.20	6.22	11.82	11.09	67.08	0.34	1.53	8.55
Net fluvial		5.97	0.13	-2.63	9.20	**12.67**	0.19	-0.31	**2.16**
Net total		-30.23	0.13	-2.63	9.20	**6.22**	-10.61	-0.31	**-4.24**

Table 11. Annual N and P inputs and outputs in different flow pathways for White Springs Bog. Values are kg N $ha^{-1}y^{-1}$ or kg P $ha^{-1}y^{-1}$. Fluvial fluxes include N and P moving in precipitation, surface and groundwater. Total fluxes include inputs in fertilizer and output in harvested berries and leaves. Positive net fluxes indicate output to the watershed, negative net fluxes indicate uptake by the watershed.

Inputs		NH_4^+	NO_3^-	DON	PON	Total N	PO_4^{3-}	Organic P	Total P
Precipitation		1.08	5.02	2.78	-	8.88	0	0	0
Surface water	Harvest flood	0.01	0.01	0.48	0.21	0.71	0.01	0.03	0.04
	Winter flood	0.01	0.01	0.36	0.15	0.53	0.01	0.04	0.05
	Irrigation—frost	0.06	0	1.09	0.08	1.23	0.06	0.12	0.18
	Irrigation—summer	0.01	0	0.18	0.70	0.89	0.01	0.02	0.03
	Irrigation—subsurface	-	-	-	-	-	-	-	-
Groundwater		0.34	0	1.02	-	1.36	0	0.24	0.24
Total fluvial input		1.51	5.04	5.91	1.14	13.60	0.09	0.45	0.54
Fertilizer		35.60	0	0	0	35.60	6.70	0	6.70
Total input		37.11	5.04	5.91	1.14	49.20	6.79	0.45	7.24
Outputs									
Surface water	Harvest flood	0.07	0.01	1.92	0.80	2.80	0.73	0.76	1.49
	Winter flood	0.01	0	0.06	0.23	0.30	0.02	0.04	0.06
	Non-flood baseflow	0.99	0.97	1.92	4.57	8.45	-	-	3.44
	Growing season storms	0	0	0.02	0.03	0.05	0	0	0
Groundwater		-	-	-	-	-	-	-	-
Total fluvial output		1.07	0.98	3.92	5.63	11.60	0.75	0.80	4.99
Harvest						33.09			4.92
Total output		1.07	0.98	3.92	5.63	44.69	0.75	0.80	9.91
Net fluvial		-0.44	-4.06	-1.99	4.49	**-2.00**	0.66	0.35	**4.45**
Net total		-36.04	-4.06	-1.99	4.49	**-4.51**	-6.04	0.35	**2.67**

Table 12. Annual N and P inputs and outputs in different flow pathways for State Bog. Values are kg kg N $ha^{-1}y^{-1}$ or kg P $ha^{-1}y^{-1.}$ Fluvial fluxes include N and P moving in precipitation, surface and groundwater. Total fluxes include inputs in fertilizer and output in harvested berries and leaves. Positive net fluxes indicate output to the watershed, negative net fluxes indicate uptake by the watershed.

Inputs		NH_4^+	NO_3^-	DON	PON	Total N	PO_4^{3-}	Organic P	Total P
Precipitation		1.08	5.02	2.78	0	8.88	0	0	0
Surface water	Harvest flood	0.13	0.03	1.07	0.70	1.93	0.06	0.19	0.25
	Winter flood	0.01	0.06	0.10	0.08	0.25	0.01	0.01	0.02
	Irrigation—frost	0.09	0	0.51	2.90	3.50	0	0.09	0.09
	Irrigation—summer	0.06	0	0.34	1.65	2.05	0	0.06	0.06
	Irrigation—subsurface	0.03	0	0.20	0.96	0.19	0	0.03	0.03
Groundwater		-	-	-	-	-	-	-	-
Total fluvial input		1.40	5.11	5.00	6.29	17.80	0.07	0.38	0.45
Fertilizer		34.70	0	0	0	34.70	4.90	0	4.90
Total input		36.10	5.11	5.00	6.29	52.50	4.97	0.38	5.35
Outputs									
Surface water	Harvest flood	0.14	0.03	2.06	1.25	3.48	0.09	0.33	0.42
	Winter flood	0.10	0	0.35	0.12	0.57	0.01	0.04	0.05
	Non-flood periods	3.82	0.16	3.25	4.94	12.17	-	-	2.07
	Growing season storms	0.04	0	0.10	0.23	0.37	0	0.06	0.06
Groundwater		0.75	0.02	0.36	0	1.13	0.16	0.04	0.20
Total fluvial output		4.85	0.21	6.12	6.54	17.72	0.26	0.47	2.80
Harvest						29.45			4.35
Total output		4.85	0.21	6.12	6.54	47.17	0.26	0.47	7.15
Net fluvial		3.45	-4.90	1.12	0.25	**-0.08**	0.19	0.09	**2.35**
Net total		-31.25	-4.90	1.12	0.25	**-5.33**	-4.71	0.09	**-1.80**

Table 13. Percentage of net total fluvial inputs and outputs of N and P to each bog that were contained in precipitation, surface water and groundwater.

			Bog		
Nutrient	Direction	Water type	Rocky Pond	White Springs	State
Nitrogen	Input	Precipitation	36	65	50
		Surface water	27	25	50
		Groundwater	37	10	0
	Output	Surface water	100	100	94
		Groundwater	0	0	6
Phosphorus	Input	Precipitation	0	0	0
		Surface water	29	56	100
		Groundwater	71	44	0
	Output	Surface water	100	100	93
		Groundwater	0	0	7

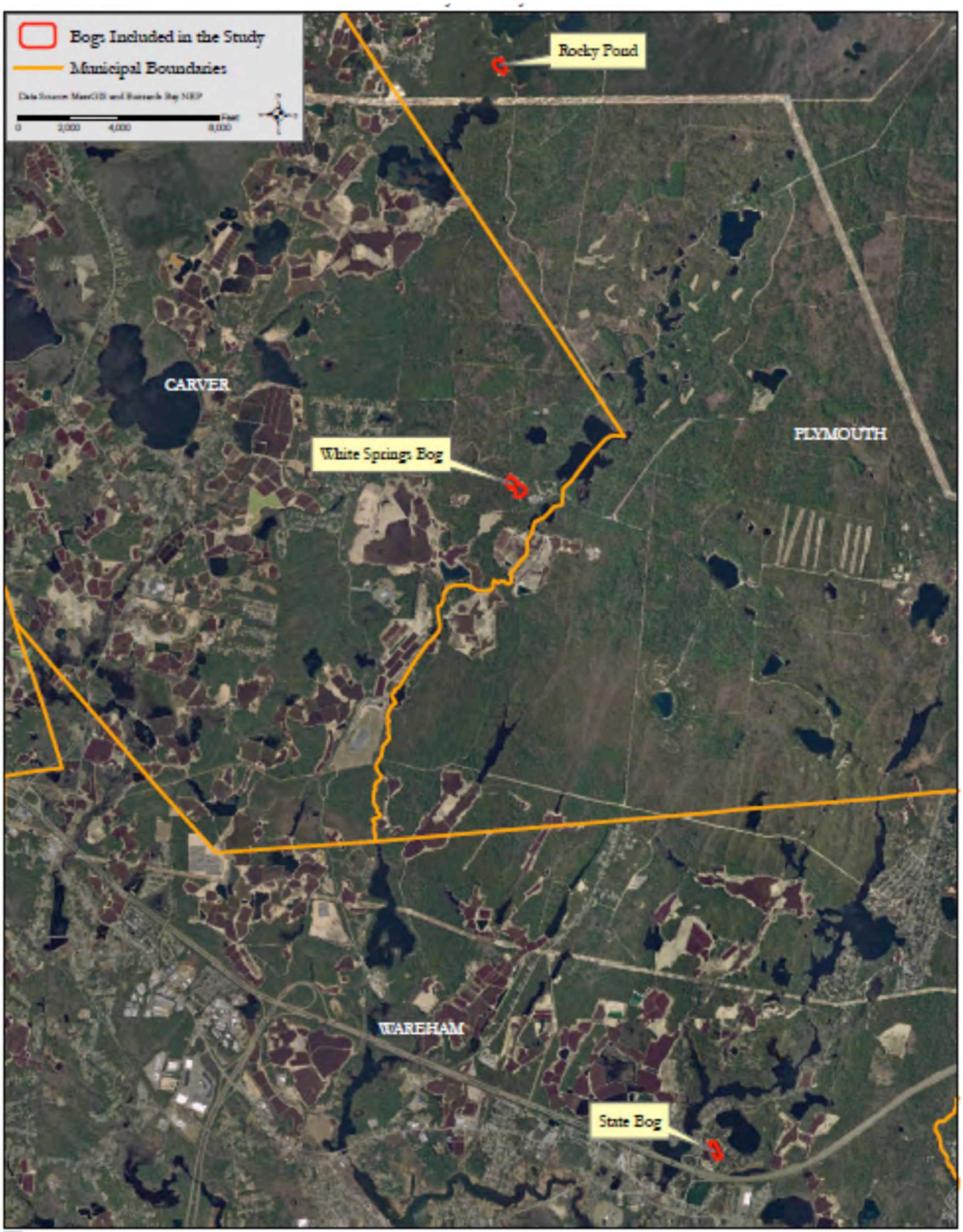
Table 14. Percentage of total fluvial N and total fluvial P inputs and outputs in precipitation and surface water and groundwater that moved during time of year in harvest floods, winter floods, irrigation and non-flood periods.

			Bog		
Nutrient	Direction	Period	Rocky Pond	White Springs	State
Nitrogen	Input	Precipitation	36	65	50
		Harvest flood	15	5	11
		Winter flood	4	4	1
		Irrigation	8	16	38
		Groundwater	37	10	0
	Output	Harvest flood	14	24	20
		Winter flood	9	3	3
		Non-flood periods	77	73	75
		Growing season rainstorms	0	0	2
Phosphorus	Input	Precipitation	0	0	0
		Harvest flood	14	7	56
		Winter flood	5	9	4
		Irrigation	11	39	40
		Groundwater	71	44	0
	Output	Harvest flood	31	30	15
		Winter flood	14	1	2
		Non-flood periods	55	69	81
		Growing season rainstorms	0	0	2

Table 15. Net N and P exchanges in harvest and winter floods and comparison with other studies. Values are kg N ha^{-1} and kg P ha^{-1}. Positive values indicate N or P export, negative values indicate N or P retention.

	Nutrient	Flood	Range
This study	N	Harvest	1.5 to 2.1
	N	Winter	-0.3 to 2.3
	N	Annual	-2.0 to 12.7
	P	Harvest	0.2 to 1.5
	P	Winter	0 to 0.5
	P	Annual	2.2 to 4.5
Town of Carver et al. 2015	N	Harvest	-4.9 to 14.6
	N	Winter	-0.6 to -0.6
	P	Harvest	0.1 to 6.4
	P	Winter	-0.4 to 1.9
DeMoranville and Howes 2005	N	Harvest	-1.2 to 9.2
	N	Winter	-6.9 to 3.6
	P	Harvest	-1.0 to 3.2
	P	Winter	-0. 5 to 1.3
Howes and Teal 1995	N	Annual	25.8
	P*	Annual	11.1
Kennedy et al. 2018	N	Annual	16.3 to 9.3
	P	Annual	3.3 to 1.3

*PO_4^{3-} alone and did not include organic P



Map prepared by: Buzzards Bay National Estuary Program, 2870 Cranberry Highway, East Wareham, MA 02538. www.buzzardsbay.org September 1, 2015.

Figure 1. Location of bog study sites. Interstate 495 is at the bottom of the image.

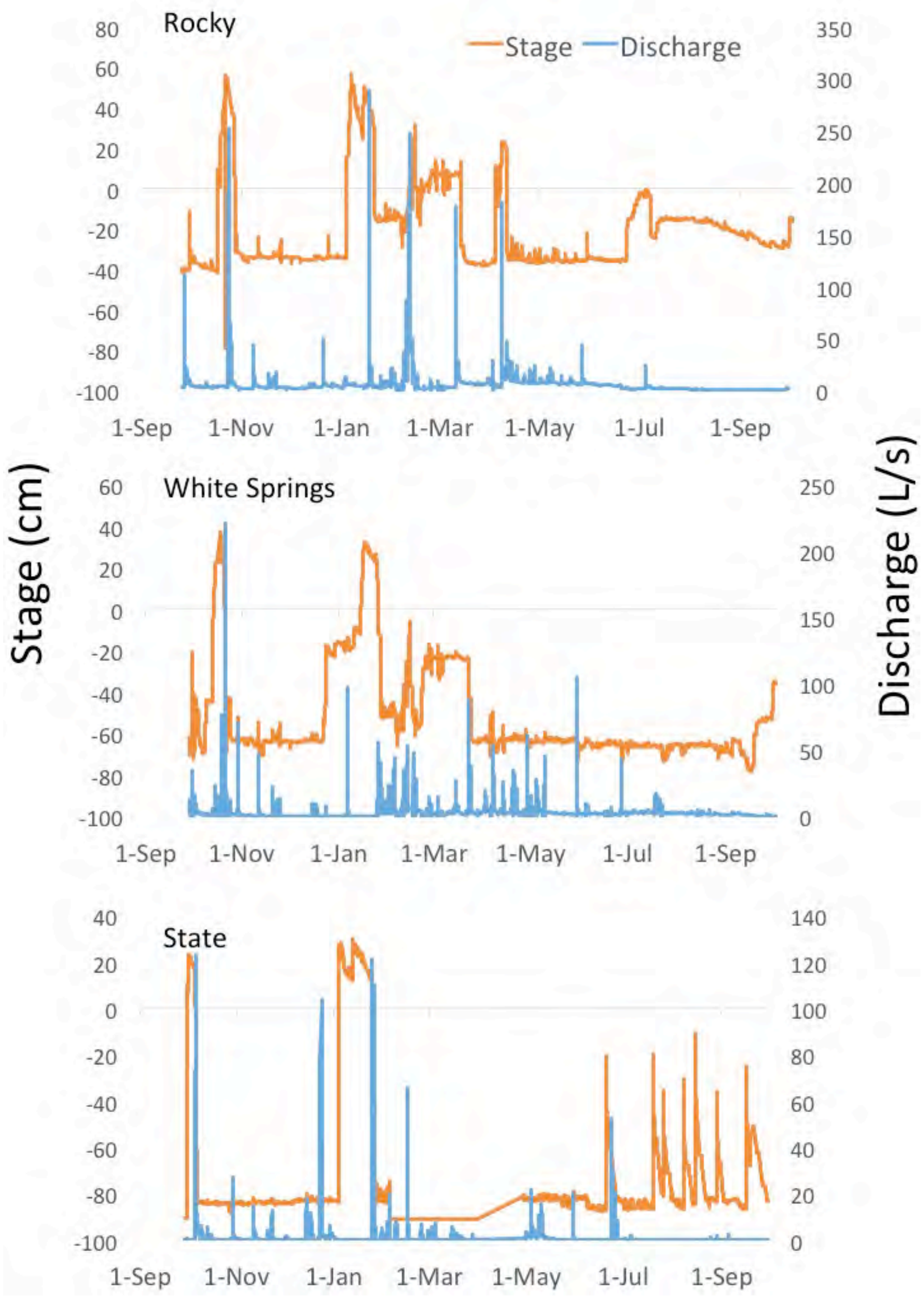


Figure 2. Bog water levels and water discharge in bog outlet channels (Rocky Pond and White Springs Bogs) or outlet water control structure (State Bog). Stage level of zero indicates the elevation of the bog platform.

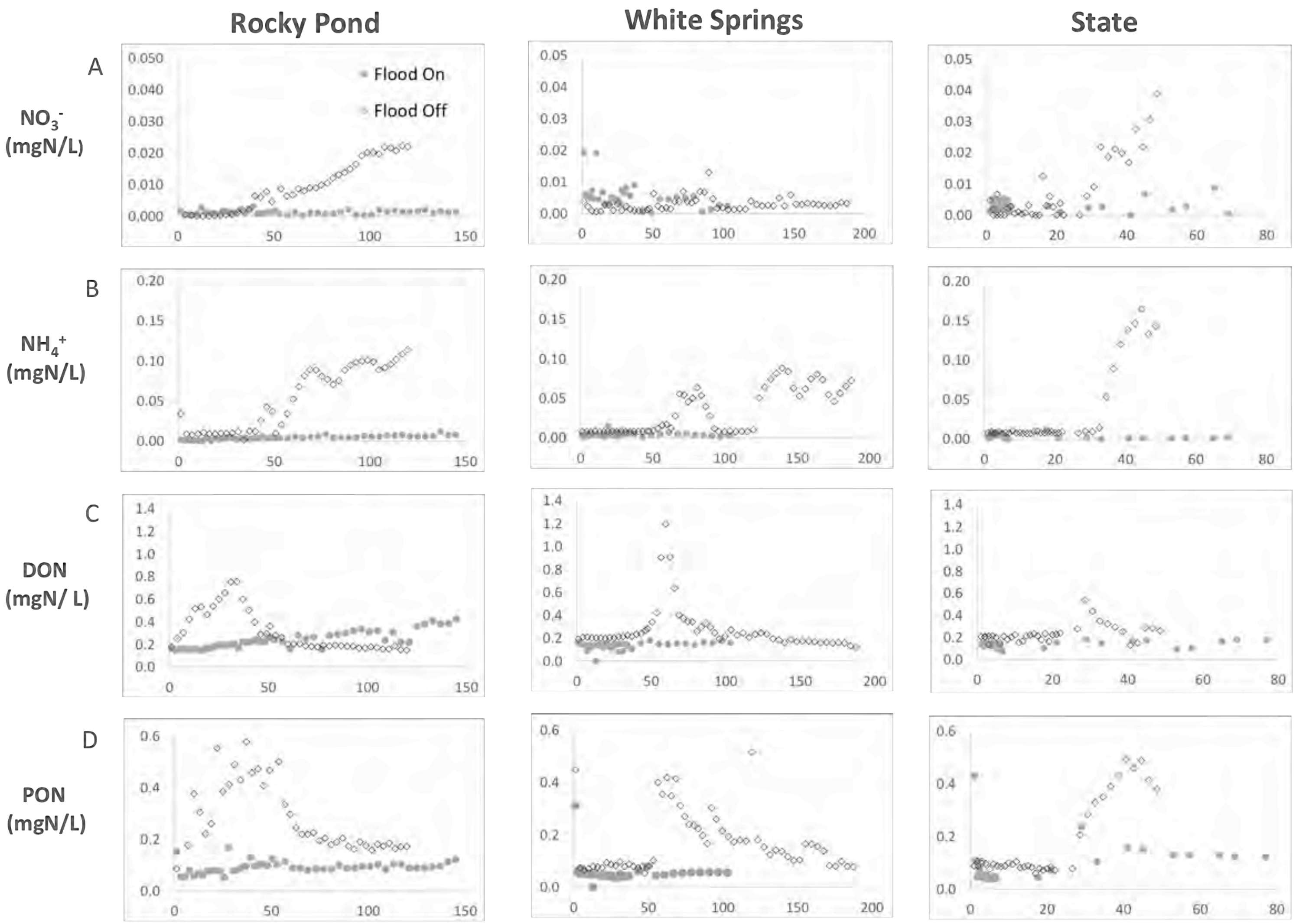


Figure 3. Dynamics of NO_3^-, NH_4^+, DON and PON concentrations in input (closed circle) and output (open circle) harvest surface floodwaters. Time zero indicates initiation of sample collection for floodwater moving on or off each bog, which was the day before active water movement began. Floodwater on and off did not occur simultaneously and floodwater remained on the bog for 7 to 14 days.

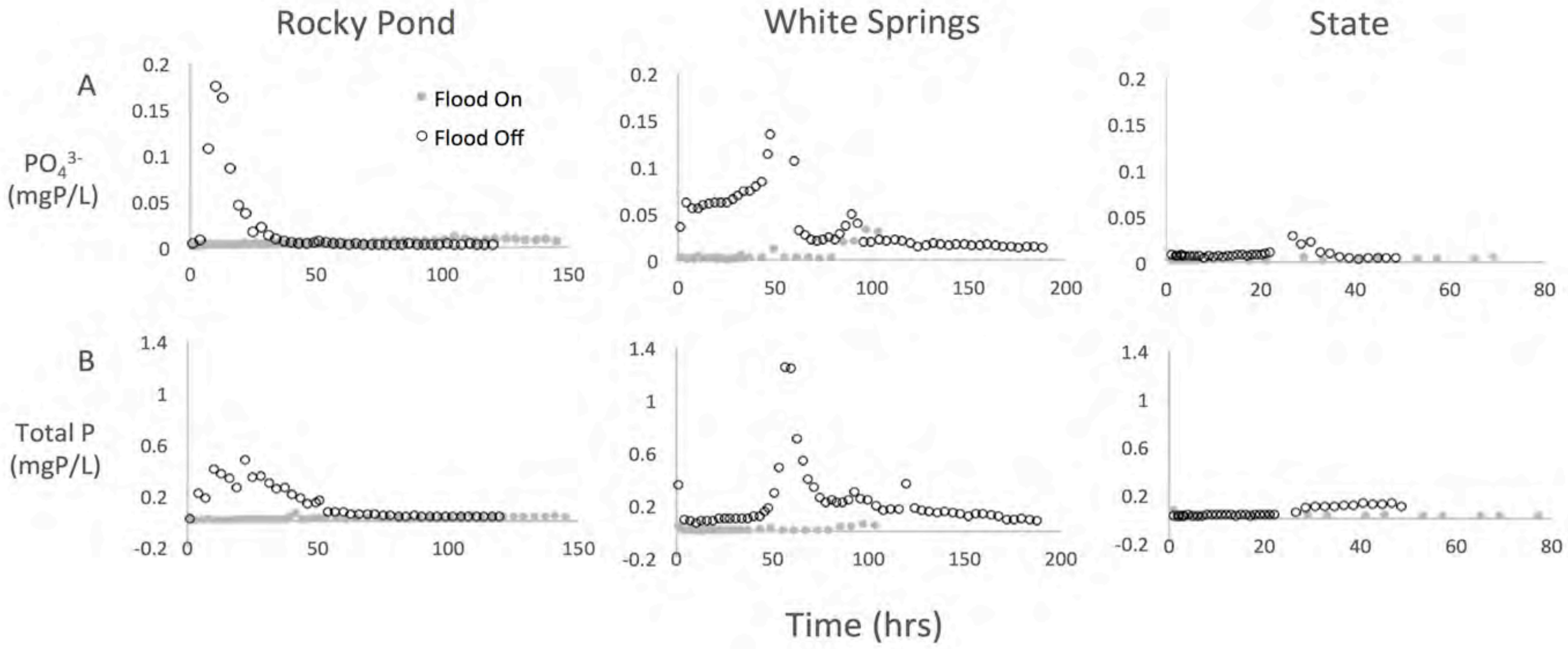


Figure 4. Dynamics of PO_4^{3-} and TP concentrations in input (closed circles) and output (open circles) harvest surface floodwaters. Time zero indicates initiation of sample collection for floodwater moving on or off each bog, which was the day before active water movement began. Floodwater on and off did not occur simultaneously and floodwater remained on the bog for 7 to 14 days.

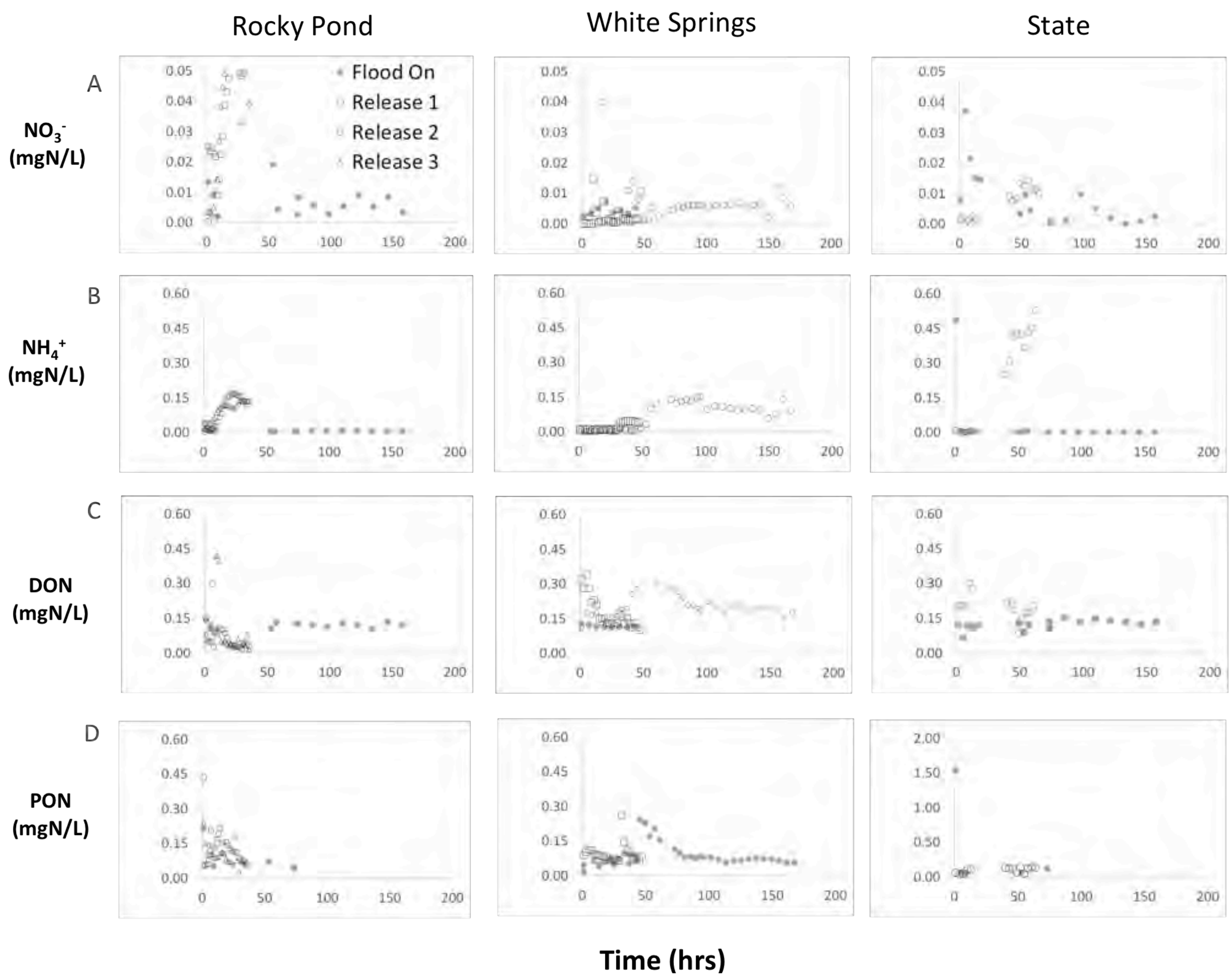


Figure 5. Dynamics of NO_3^- (A), NH_4^+ (B), DON (C), and PON (D) concentrations in input (closed circles) and output (open symbols) winter surface floodwaters. Rocky Pond and White Springs Bogs had multiple winter floods.

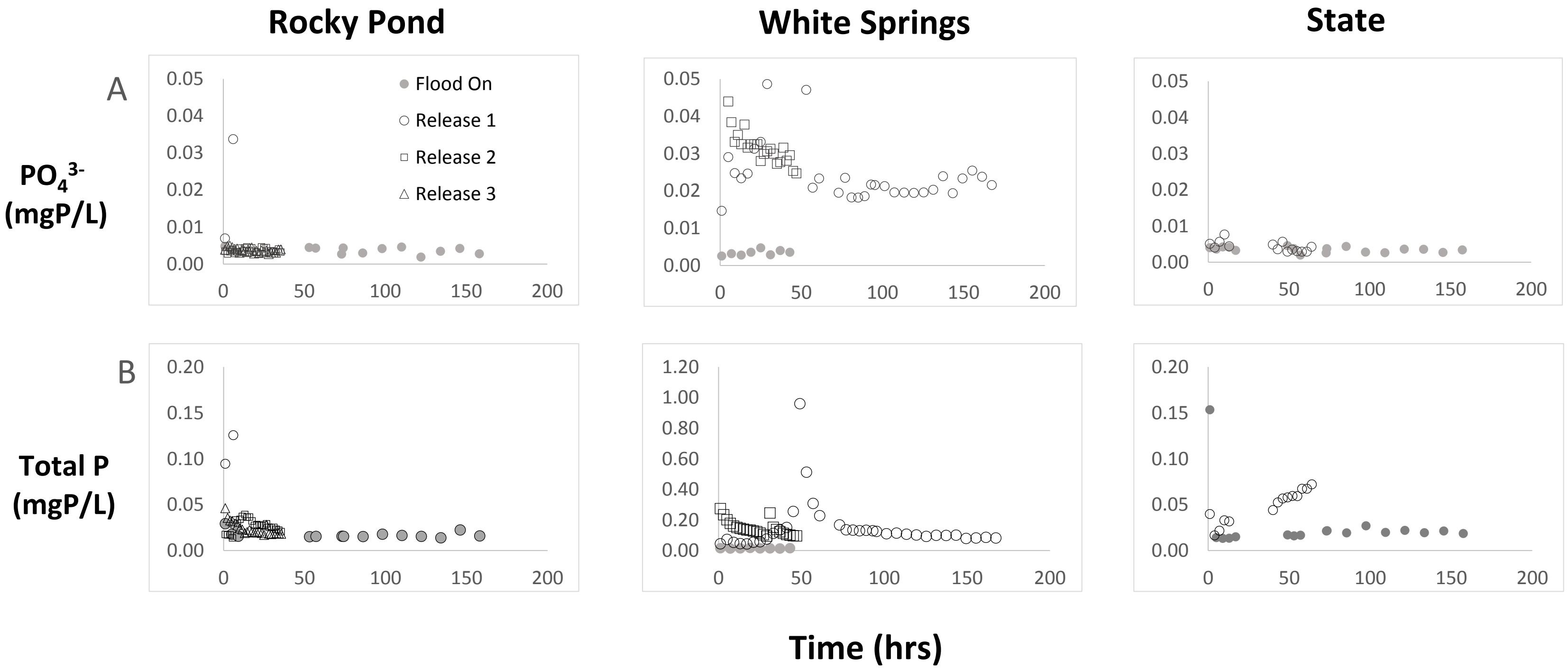


Figure 6. Dynamics of PO_4^{3-} (A) and TP (B) concentrations in input (closed circles) and output (open symbols) winter surface floodwaters. Rocky Pond and White Springs Bogs had multiple winter floods.

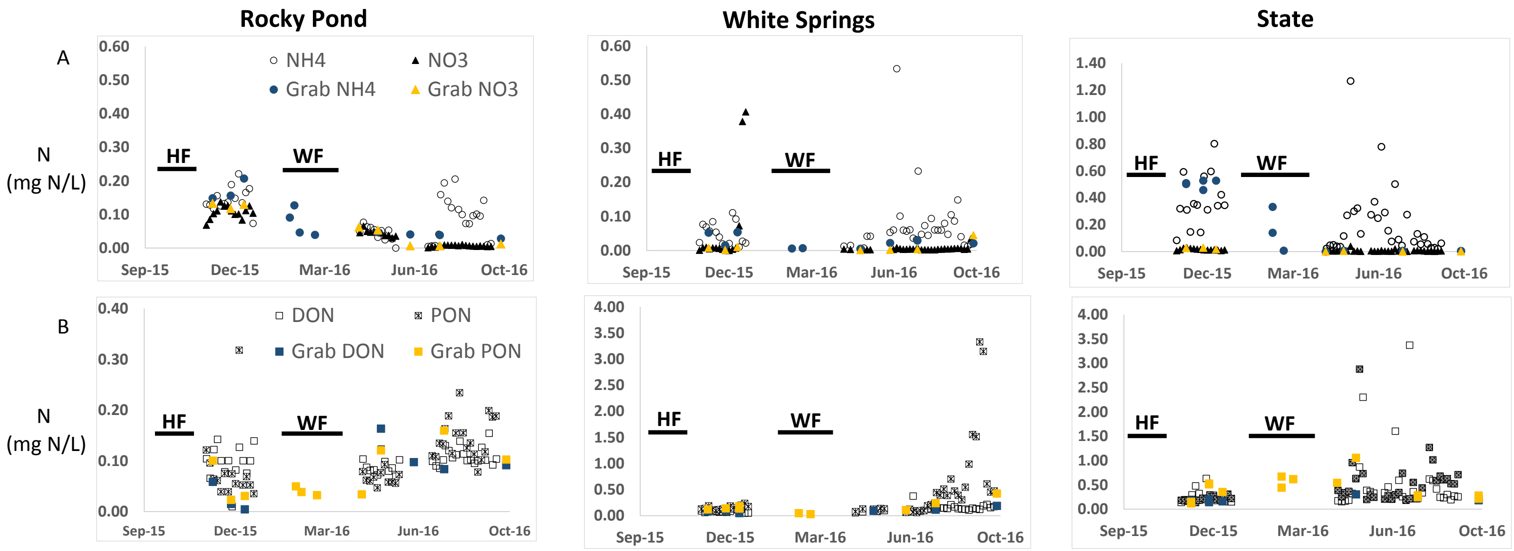


Figure 7. Concentrations of dissolved inorganic NO_3^-, NH_4^+ (A), and DON and PON (B) measured from four-day composite samples of bog outlet surface waters collected with Isco automatic samplers. Bars show periods of harvest floods (HF) and winter floods (WF) that were sampled separately. Samples were preserved with sulfuric acid in the bottles after collection. Concentrations of NO_3^-, NH_4^+, DON and PON in grab samples that accompanied automatically-collected and preserved sample are also plotted.

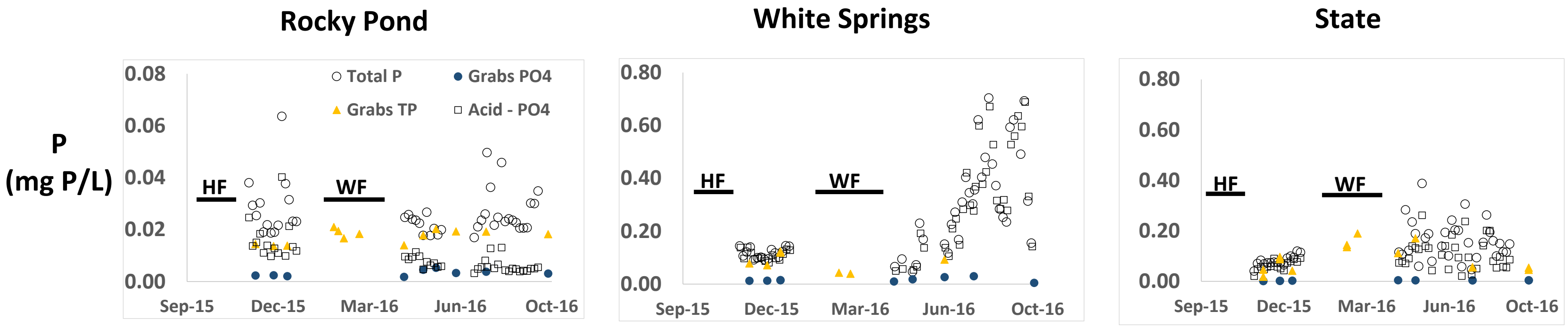


Figure 8. Concentrations of PO_4^{3-} and TP measured from four-day composite sampling of bog outlet surface water collected with Isco automatic samplers and preservative. Concentrations of PO_4^{3-} and TP in grab samples that accompanied automatically-collected and preserved sample are also plotted.

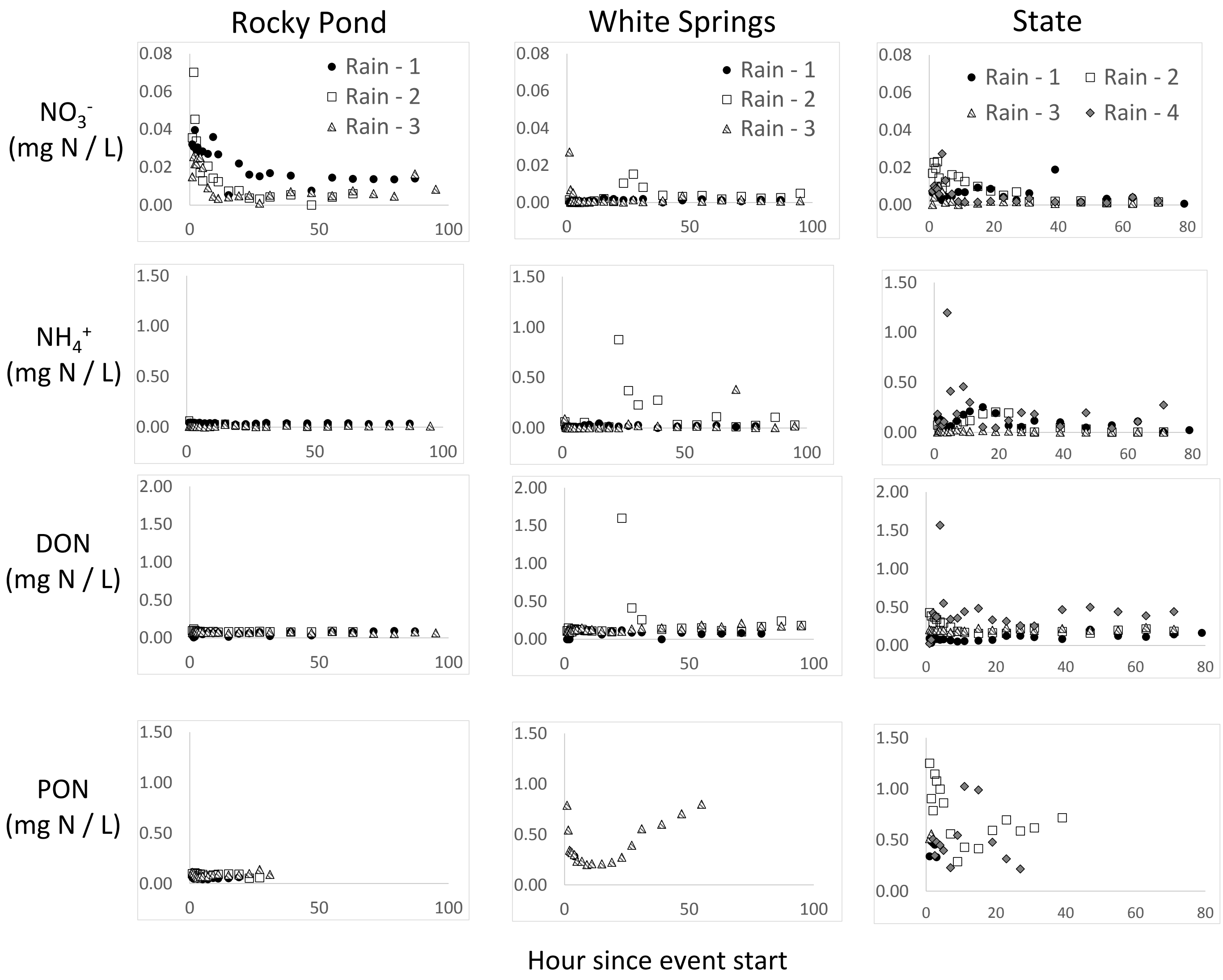


Figure 9. Concentrations of NH_4^+, NO_3^-, DON and PON in outflowing surface water following growing season rainfall events.

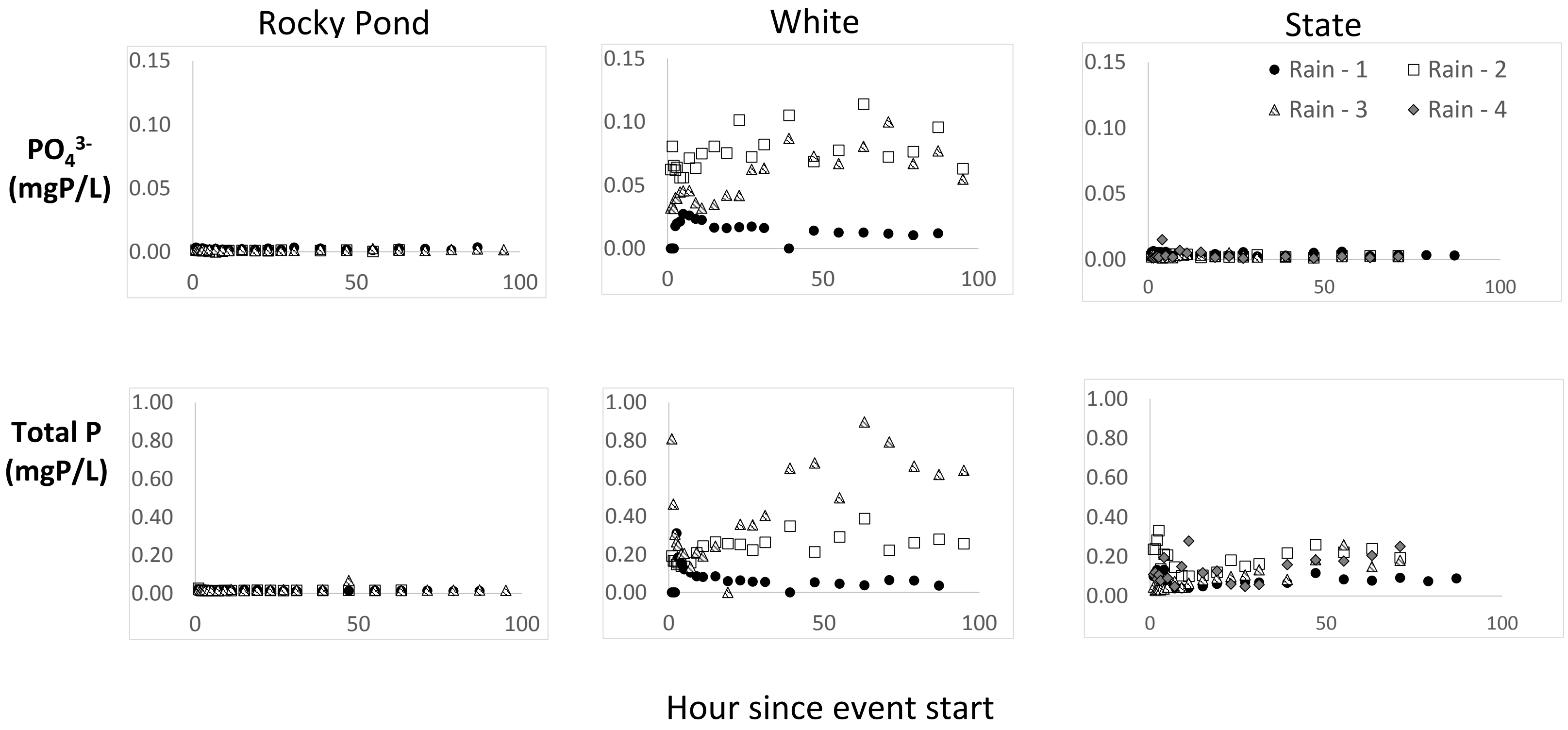


Figure 10. Concentrations of PO$_4^{3-}$ and TP in outflowing surface water following growing season storm events

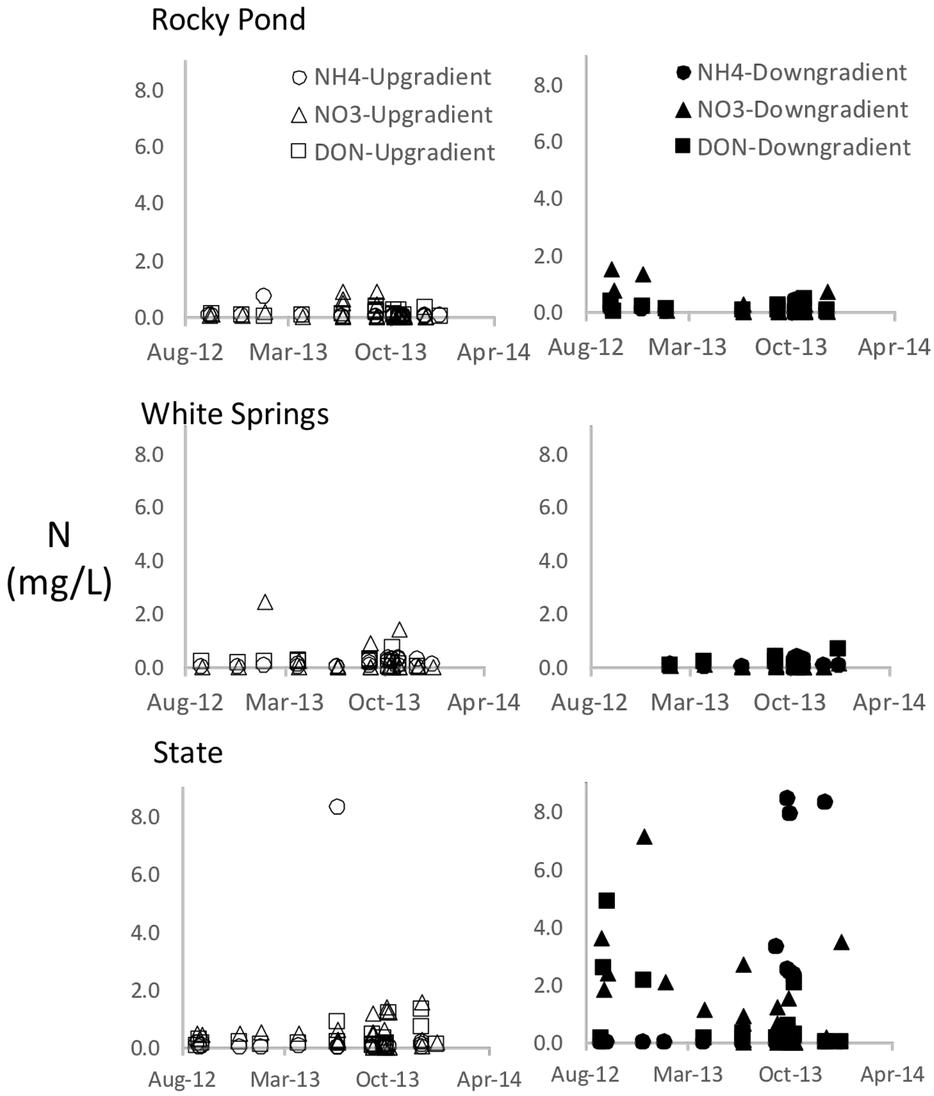


Figure 11. Concentrations of NO_3^-, NH_4^+ and DON in upgradient and downgradient groundwater over time.

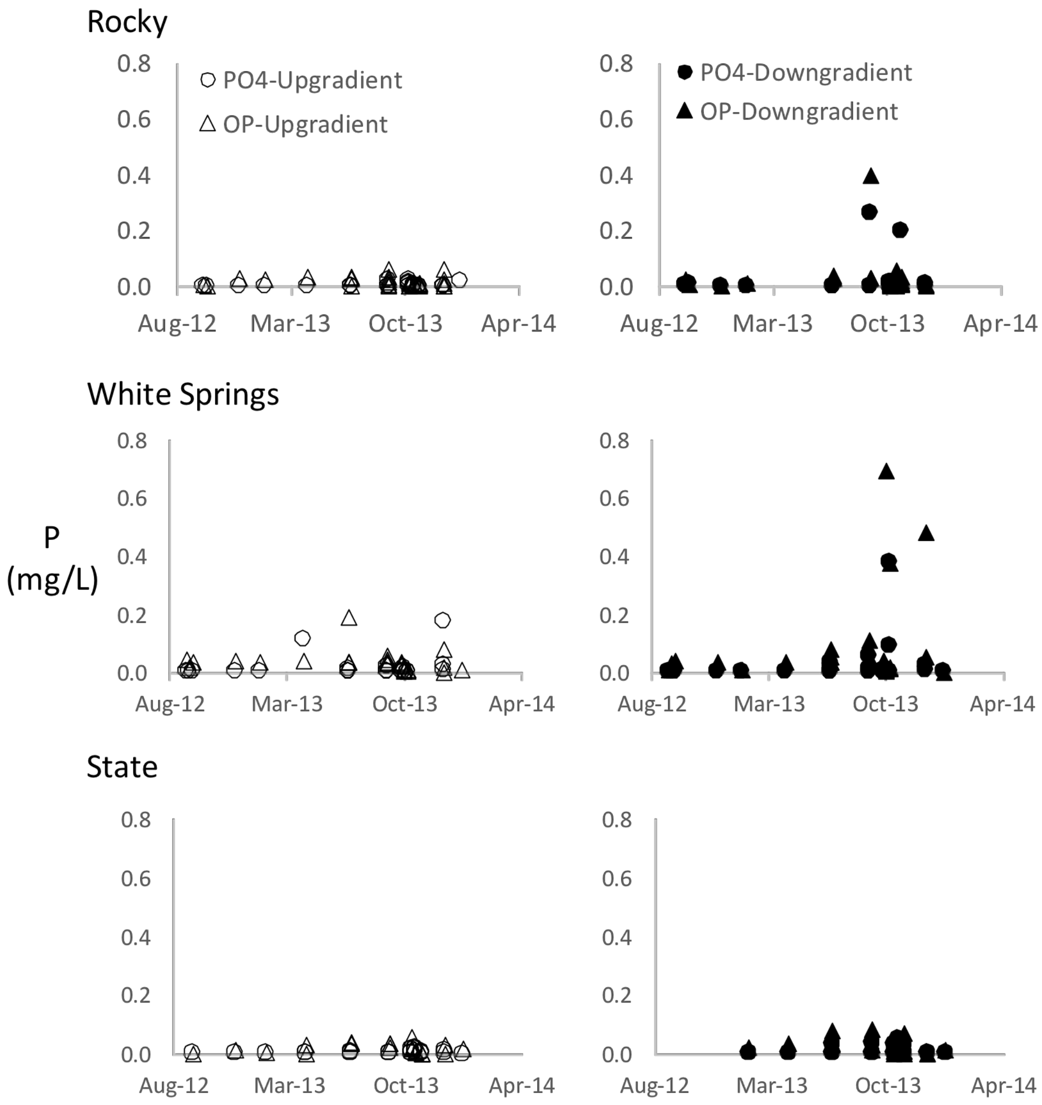


Figure 12. Concentrations of PO_4^{3-} and TP in upgradient and downgradient groundwater wells measured over time.

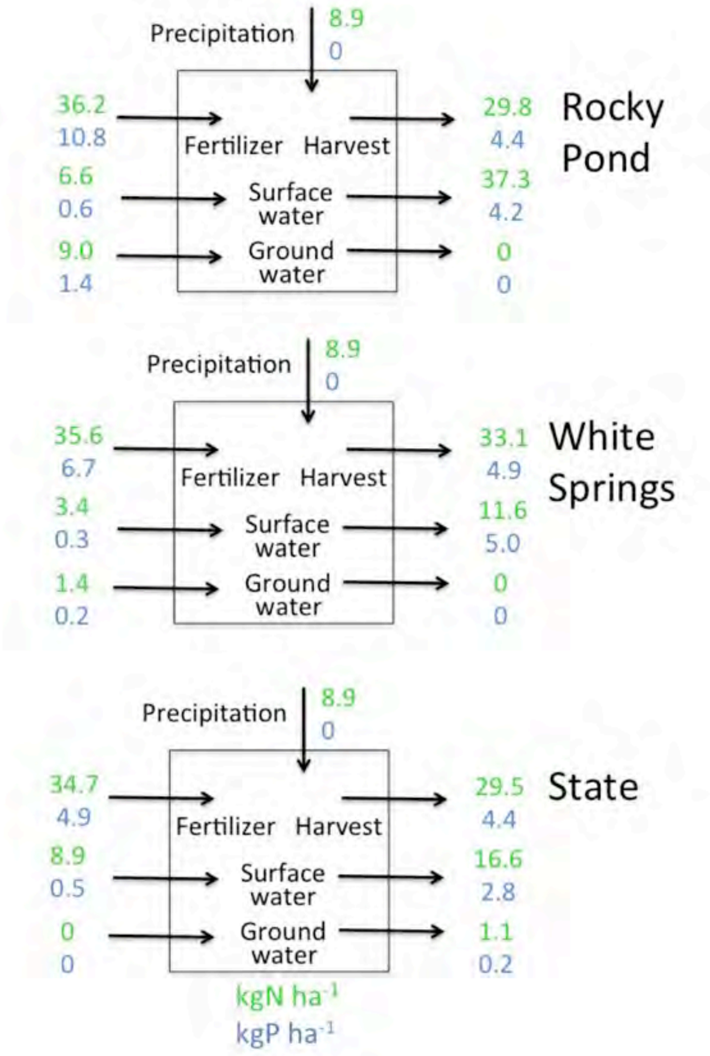


Figure 13. Summary of total N and P inputs in precipitation, fertilizer, surface water and groundwater, and total N and P outputs in berry harvest, surface water and groundwater. Units are kg N ha^{-1} (green) and kg P ha^{-1} (blue).