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Hydrologic and nutrient response of groundwater to flooding of cranberry farms in southeastern Massachusetts, USA

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SUMMARY

Seasonal flooding of cranberry farms is essential for commercial production of cranberries in southeastern Massachusetts, with close to 90% of growers using a flood for harvesting and winter protection. Although periodic flooding results in increased groundwater recharge, it may also exacerbate subsurface transport of dissolved forms of nitrogen and phosphorus. Given the paucity of information on groundwater exchange with cranberry floodwaters, hydrometric measurements were used to solve for the residual term of groundwater recharge in water budgets for three cranberry farms during the harvest and winter floods. Combined with continuous monitoring of water-table depth and discrete sampling of groundwater for analysis of nitrate (NO_3^-), ammonium (NH_4^+), and total dissolved phosphorus (TDP), values of groundwater recharge were used to evaluate the hydrologic and nutrient response of groundwater to flooding of cranberry farms. Mean values of groundwater recharge were 11 (±6) and 47 (±11) cm for the harvest and winter floods, respectively (one standard deviation in parentheses). The factor-of-four difference in ground recharge was related to flood holding times that, on average, were twenty days longer for the winter flood. The total estimated seasonal groundwater recharge of 58 cm was about four times higher than that assigned to cranberry farms in regional groundwater flow models. During the floods, 10 to 20-cm increases in water-table depth were observed for wells within 10 m of the farm, contrasting with decreases (or minimal variation) in water-table depth for wells located 100 m or farther from the farm. These spatial patterns in the hydrologic response of groundwater suggested a zone of influence of approximately 100 m from the flooded edge of the farm. Analysis of 43 groundwater samples collected from 10 wells indicated generally low concentrations of TDP in groundwater (<0.32 μM for 84% of the samples). Nitrate accounted for 85% of the dissolved inorganic N in groundwater, exhibiting a spatial pattern of decreasing concentration with increasing distance from the farm (e.g., values were consistently less than 3.6 μM for wells located ~100 m from the flooded edge of farms). For one groundwater well located in proximity to the farm (~10 m), decreases in NO_3^- concentration from 565 μM (pre-flood) to 99 μM (post-flood) were consistent with winter floodwater as a source of low-NO_3^- groundwater recharge.

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1. Introduction

The cranberry industry occupies a unique place in the history of southeastern Massachusetts (MA), where commercial production of cranberries has existed for close to two centuries (Eck, 1990). Seasonal flooding of cranberry farms is essential for long-term sustainability of cranberry production in southeastern MA, with roughly 90% of growers using a flood to protect the plants from desiccation in the winter and to harvest the fruit in the fall (DeMoranville, 2008a). For both the harvest and winter floods, 30–60 cm of surface water is generally moved onto the farm, held for days to months, then released to a lake or stream. In MA, growers commonly apply a winter flood between December and January, releasing the flood not later than mid-March (DeMoranville, 2008a). The cranberry harvest typically occurs in October, with the harvest flood usually held for several days (DeMoranville, 2008a).

While floods represent important management tools, quantitative estimates of groundwater recharge derived from cranberry floodwaters are lacking. Cranberry farms represent one of five types of recharge to the Plymouth–Carver–Kingston–Duxbury (PCKD) aquifer system (Masterson et al., 2009), an unconfined

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aquifer composed of highly-permeable glacially deposited sediments and designated a Sole Source Aquifer by the U.S. Environmental Protection Agency. In a study of nitrogen export from a cranberry farm, Howes and Teal (1995) reported decreases in flood height of 10 cm and increases in groundwater levels of 17 cm located within 16 m of the flooded edge of the bog, suggesting groundwater exchange with cranberry floodwaters. Groundwater flow models for the PCKD aquifer have assumed that cranberry farms function as wetlands except during the months of October and December, when harvest and winter flooding accounts for an additional 5 cm of groundwater recharge derived from cranberry farms (Masterson et al., 2009).

As with water quantity, water quality poses a serious threat to the long-term sustainability of the MA cranberry industry, reflected by state and federal activities within the state's major cranberry producing area, the Buzzards Bay Basin (MassDEP, 2012) (Fig. 1A). Regionally, cranberries are cultivated on wetlands, which are often perceived to improve water quality through nutrient retention and transformation (Reddy et al., 1984, 1999), but their capacity to enhance water quality may diminish in response to nutrient loadings from agriculture (Howes and Teal, 1995). Although recommended fertilizer application rates for cranberry (22–67 kg N ha^{-1} yr^{-1}, 11–22 kg P ha^{-1} yr^{-1}) are relatively low compared to other crops, such as corn (179–224 kg N ha^{-1} yr^{-1}, 28–73 kg P ha^{-1} yr^{-1}) (Davenport et al., 2000; DeMoranville, 2008b, 2014), they represent a source of nutrients vulnerable to leaching to groundwater, particularly in response to increased groundwater recharge from flooding.

The chemistry of cranberry soils, particularly the high iron (Fe) and aluminum (Al) of acidic soils, results in extensive binding of P as Fe and Al compounds in soils (Davenport and DeMoranville, 1997). However, flooded cranberry soils may lead to anaerobic conditions that mobilize iron-bound P (DeMoranville, 2006; DeMoranville et al., 2009). Although ammonium-based fertilizers are widely used by the MA cranberry industry, aerated sandy soils generally result in nitrification of ammonium (NH_4^+) to nitrate (NO_3^-), which is one of the most ubiquitous and persistent agricultural contaminants found in shallow groundwater (Böhlke, 2002). The anaerobic conditions that promote the mobilization of P in cranberry soils, however, may also facilitate the reduction of NO_3^- via denitrification during floods (Reddy et al., 1984). The competing physical and chemical factors affecting subsurface transport of N and P points to the need for monitoring programs designed to quantify both spatial and temporal variations in the nutrient response of groundwater to flooding.

In this study, groundwater recharge derived from flooding of cranberry farms was quantified and its effect on N and P concentrations in groundwater assessed. For three cranberry farms, hydrometric measurements were used to solve for the residual term of groundwater recharge in water budgets for cranberry farms during the harvest and winter floods. Additionally, continuous measurements of water-table depth and discrete sampling of groundwater

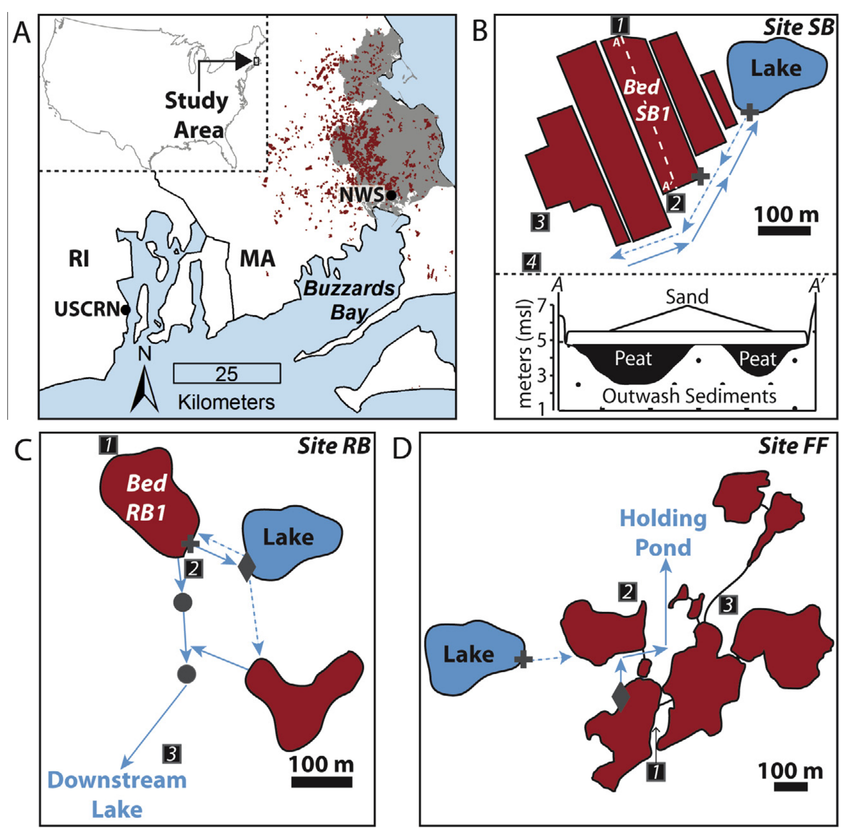

Fig. 1. Area map with locations of the National Weather Service (NWS) and U.S. Climate Reference Network (USCRN) stations in East Wareham, MA and Kingston, RI, respectively (A). The dark gray area, covering most of southeastern MA, represents the groundwater contributing area of the Plymouth–Carver–Kingston–Duxbury Aquifer System (Masterson et al., 2009), and the distribution of cranberry farms is shown in red (MassDEP, 2009). Map of farm SB and cross-sectional view of cranberry bed SB1 (B). Peat stratigraphy is based on results from a ground penetrating radar survey of site SB (Doolittle et al., 1990; NESOIL, 2014). Depth to sand layer was measured in the cranberry bed using standard auger techniques. Site elevations were measured by a local engineering and land surveying company as part of the site renovation in 2006 (Cindie Aadland, G.A.F. Engineering, East Wareham, MA, pers. comm., December 2013). Maps are also given for sites RB (C) and FF (D). Symbols represent locations of flow meters (cross = acoustic doppler current meter, circle = H-flume, diamond = in-line propeller meter) and groundwater wells (square). Numbers are used to identify groundwater wells (see text). Blue arrows depict the general direction of surface water inflow (dotted line) and outflow (solid line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)