



Differentiating transpiration from evaporation in seasonal agricultural wetlands and the link to advective fluxes in the root zone



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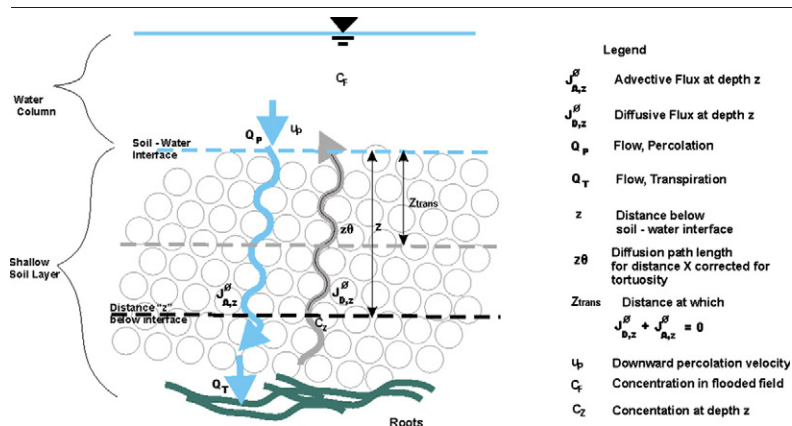
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HIGHLIGHTS

- PFR model utilizes EC as conservative tracer to calculate transpiration rates.
- Wetland transpiration causes significant summertime percolation into the root zone.
- A Peclet number equivalent relationship is derived for evaluating root zone fluxes.
- Transpiration affects soil diffusive and advective flux vertical distribution.
- Transpiration causes seasonal/diel trends in benthic fluxes of Hg and other constituents.

GRAPHICAL ABSTRACT



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ABSTRACT

The current state of science and engineering related to analyzing wetlands overlooks the importance of transpiration and risks data misinterpretation. In response, we developed hydrologic and mass budgets for agricultural wetlands using electrical conductivity (EC) as a natural conservative tracer. We developed simple differential equations that quantify evaporation and transpiration rates using flow rates and tracer concentrations at wetland inflows and outflows. We used two ideal reactor model solutions, a continuous flow stirred tank reactor (CFSTR) and a plug flow reactor (PFR), to bracket real non-ideal systems. From those models, estimated transpiration ranged from 55% (CFSTR) to 74% (PFR) of total evapotranspiration (ET) rates, consistent with published values using standard methods and direct measurements. The PFR model more appropriately represents these non-ideal agricultural wetlands in which check ponds are in series. Using a flux model, we also developed an equation delineating the root zone depth at which diffusive dominated fluxes transition to advective dominated fluxes. This relationship is similar to the Peclet number that identifies the dominance of advective or diffusive fluxes in surface and groundwater transport. Using diffusion coefficients for inorganic mercury (Hg) and methylmercury (MeHg) we calculated that during high ET periods typical of summer, advective fluxes dominate root zone transport except in the top millimeters below the sediment–water interface. The transition depth has diel and seasonal trends, tracking those of ET. Neglecting this pathway has profound implications: misallocating loads along different hydrologic pathways; misinterpreting seasonal and diel water quality trends; confounding Fick's First Law calculations when determining diffusion fluxes using pore water concentration data; and misinterpreting biogeochemical mechanisms affecting dissolved constituent cycling in the root zone. In addition,

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our understanding of internal root zone cycling of Hg and other dissolved constituents, benthic fluxes, and biological irrigation may be greatly affected.

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1. Introduction

In wetlands, transpiration accounts for between 50 and 90% of the total ET during a growing season (Herbst and Kappen, 1999; Sanchez-Carrillo et al., 2004; Bouman et al., 2005). It is an important vector for moving constituents from the water column into the root zone in shallow aquatic systems (Howes et al., 1986; Hayashi et al., 1998; Reddy et al., 1999; Kadlec, 1999; Whitmer et al., 2000; Parsons et al., 2004; van der Kamp and Hayashi, 2009). Dacey and Howes (1984) determined transpiration as the primary cause for downward movement of the water table during both day and night in the short grass zone in intertidal salt marshes. Rosenberry et al. (2013) report that seepage in a Minnesota lake changed 10% during the day in response to ET withdrawals. Using a Br tracer study in a seasonal wetland, Parsons et al. (2004) found that less than 10% of the Br initially released was taken up by plants and most of the Br was transported into the upper 40–80 cm of the wetland soil surface. They describe how ET drives infiltration rates in seasonal wetlands, with infiltration rates increasing during summer periods of high evaporation. In a review paper on prairie wetlands of northern USA and Canada, van der Kamp and Hayashi (2009) describe how infiltration in the upper few meters of those wetlands is driven by evaporation and root uptake. A number of constituent cycling studies using bromide (Br) tracers have shown applied Br concentrating in the soil root zone and plant tissues (Howes et al., 1986; Whitmer et al., 2000; Parsons et al., 2004).

Transpiration has also been linked to transport and release of mercury (Hg) and volatile organic compounds from wetlands. Lindberg et al. (2002) determined that the flux of elemental Hg vapor (Hg^0) from rooted emergent cattail and sawgrass wetlands in the Florida Everglades significantly exceeded emissions from non-vegetated areas and from uprooted (floating) stands. A strong correlation with water vapor suggested transpiration as the driving mechanism. Mercury vapor fluxes exhibited a diel cycle with two peaks, and Lindberg et al. (2002) proposed two different gas exchange dynamics: early morning lacunal gas releases and midday transpiration releases. Lindberg et al. (2005) concluded that Hg^0 emitted from emergent macrophytes originates as inorganic Hg^{2+} in the sediments where it is reduced to Hg^0 ; they confirmed the two processes earlier proposed by Lindberg et al. (2002). Their mass balance calculations estimated that a release of Hg^0 is 1 kg yr^{-1} from a 1500 ha wetland, 20 times the amount evaded from the water surface. Reid and Jaffé (2012) found a similar result with emissions of volatile organic compounds from wetlands to be linked with transpiration.

Despite its physical role in vegetated systems, transpiration is not often included in the wetland biogeochemistry literature in consideration of benthic fluxes. Root hairs provide a large surface area that moves water from soil to plants (Raven et al., 1999). During periods of rapid transpiration, soils adjacent to the root zone may lack sufficient water, resulting in a hydraulic pressure gradient moving water towards root hairs (Taiz and Zeiger, 1991; Raven et al., 1999). This bulk movement of water is an advective process. Yet, benthic flux, defined as the transport of dissolved constituents between the water column and the underlying sediments, has included as transport mechanisms bioturbation, advection from biological irrigation, and diffusion (Kuwabara et al., 1999). Bioturbation is important in wetland systems (Fanjul et al., 2011; Kuwabara et al., 2012), affecting both the direction and magnitude of benthic flux between the water column and sediments by its effect on benthic metabolism and nutrient cycling (Fanjul et al., 2011). While some arid wetland research has implied the phenomenon of “biologic tides” from daily transpiration (e.g. Childers et al., Arizona State University, unpublished data),

advective flux has largely been linked to natural biological irrigation in which benthic organism activities enhance the exchange of interstitial pore water over pure diffusion (Choe et al., 2004; Hammond et al., 1985). Reddy et al. (1999) and Kadlec (1999) do discuss transpiration's role in moving nutrients into the root zone through bulk water movement. In wetland systems, diffusive flux of Hg from the sediment column to the water has been primarily assessed by chamber flux measurements and modeled by concentration gradients (Gill et al., 1999; Holmes and Lean, 2006; Rothenberg et al., 2008), similar to many other dissolved constituents (Krottje, 1980; Reddy et al., 1980, 1984; Dunne et al., 2010). Both diffusive fluxes and biological irrigation have been measured to determine benthic fluxes of methylmercury (MeHg) and total mercury (THg) from San Francisco Bay Delta sediments into the water column in tributary streams, waterways and open water (Choe et al., 2004).

The wetland biogeochemistry literature also does not adequately consider transpiration and its role with regard to advective transport from the water column to the sediments in the development of water and mass balances. Though methods exist to directly or indirectly determine evaporation and transpiration separately in agricultural wetlands (Bethune et al., 2001; Bouman et al., 2005, 2007), most wetland studies, and water or mass balance analyses aggregate these two terms into ET (Mitsch and Gosselink, 1993; Kadlec and Knight, 1996; Kadlec, 2000; Bethune et al., 2001; Carleton et al., 2001; Martinez and Wise, 2003; Playan et al., 2008) despite these being very different hydrologic and transport processes. Whether implicit or explicit, this assumption is dominant in foundational literature (Mitsch and Gosselink, 1993; Kadlec and Knight, 1996) as well as in the development of reactor models (Metcalf and Eddy, 2009; Kadlec, 1994, 2000; Werner and Kadlec, 2001; Martinez and Wise, 2003; Persson and Wittgren, 2003; Carleton and Montas, 2009), and quantification of benthic flux (Romkens and Bruce, 1964; Krottje, 1980; Reddy et al., 1980, 1984; Gill et al., 1999; Langer et al., 2001; Holmes and Lean, 2006).

Not differentiating evaporation and transpiration flow paths may generate large errors in quantifying Hg budgets and within-agricultural wetland cycling and storage processes. As part of a multi-disciplinary process-based study of Hg cycling on wetlands of California's Central Valley, we assessed hydrologic flows on six agricultural wetlands and two naturally vegetated managed wetlands over a full annual cycle. Our initial analyses did not differentiate between evaporation and transpiration. The resulting hydrologic budget was inconsistent with chloride and isotope mass budgets, thus affected our analyses of Hg cycling in the systems. Our inability to reconcile the calculations made us reassess the approach, especially concerning downward advection by root-driven transpiration and its effect on subsurface transport and cycling.

We hypothesized 1) that transpiration-driven advection provides a significant transport pathway to the root zone during the summer months, and 2) that this process leads to seasonal and diel changes in concentrations of conservative tracers, thus potentially affecting concentrations and speciation of Hg as well. To address the first hypothesis and quantify transpiration and evaporation pathways, we integrated a hydrologic balance with an electrical conductivity (EC) mass balance. We used wetland hydrologic and water quality data from the crop year May 2007–May 2008 in these models. Electrical conductivity (EC) was used as a natural conservative tracer, similar to what has been done with salts in other systems (Hayashi et al., 1998; Whitmer et al., 2000; Parsons et al., 2004; Pellerin et al., 2007). We applied two different mass balance models to assess water dynamics in the eight study wetlands. These two ideal models represented two extremes for surface water mixing: (1) a plug flow reactor (PFR) model that assumes no mixing along the flow gradient and (2) a continuous flow stirred tank reactor (CFSTR) model that assumes

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