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Effects of evapotranspiration on treatment performance in constructed wetlands: Experimental studies and modeling

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ABSTRACT

Evapotranspiration (ET) can affect treatment performance on constructed wetlands by enhancing constituent transport through the hydrosoil where treatment reactions occur. Additionally, ET can decrease volumetric flow thereby increasing hydraulic retention time and increasing concentrations of dissolved constituents. This research aims to assess the net effects of water loss attributed to ET on constructed wetland performance and determine the significance of plant transpiration on vertical transport of constituents. A flowing wetland lysimeter constructed using 265-L storage containers filled with sand and *Typha latifolia* was used to record ET and determine crop coefficient during summer 2011. Results indicate that ET from the lysimeter was 2.5 times greater than calculated reference ET ($K_c = 2.5$; $R^2 = 0.96$). The calculated crop coefficient was used in conjunction with a first-order tank-in-series model to predict removal of a conservative constituent ($k = 0.2\ d^{-1}$) and readily treatable constituent ($k = 1.2\ d^{-1}$) in a constructed wetland (20 cm and 40 cm water depths, 4-day nominal HRT, and 100 mg L^{-1} constituent loading) operating under a range of ET (0, 10, 20, and 30 mm d^{-1}). The model predicts that removal efficiency of the conservative constituent decreases with increasing ET, while removal efficiency of the readily treatable constituent increases with increasing ET. In addition, eight vertical tracer tests were performed on wetland cells with either trimmed or untrimmed *T. latifolia* to measure transport time of tracer solution from the water surface to a depth of 5 cm. Mean tracer arrival time differed significantly ($p = 1.2 \times 10^{-8}$) between the untrimmed and trimmed cells (104 min versus 450 min, respectively) demonstrating that plant transpiration contributes significantly to vertical flow through hydrosoil.

1. Introduction

Water loss in constructed wetland treatment systems (CWTSs) occurs primarily through the combined effects of open water evaporation and plant transpiration, collectively termed evapotranspiration. Because CWTSs are typically constructed with a lined bottom to prevent infiltration of contaminated water to underlying soil, evapotranspiration is a key component of the water balance. Evapotranspiration is driven primarily by the transformation of insolation energy to latent heat of vaporization of liquid water.

Numerous studies have been performed to quantify evapotranspiration from wetlands containing *Typha latifolia* (i.e. broadleaf cattails) with conflicting results attributed to differing measurement methods and lysimeter designs (Allen et al., 1992, 1997; Anderson and Idso, 1987; Idso and Anderson, 1988; Otis, 1914; Idso, 1981; Snyder and Boyd, 1987; Towler et al., 2004). As explained by Idso and Anderson (1988), evapotranspiration can be influenced by the "oasis effect" (Shaw, 1967) resulting in elevated evapotranspiration from isolated, small stands of vegetation compared to large expanses of vegetation. Incoming latent heat from surrounding dry fetch is advectively exchanged through the periphery of isolated stands of vegetation, leading to an increase in incoming energy and corresponding increase in evapotranspiration (Idso and Anderson, 1988; Towler et al., 2004). Evapotranspiration is also dependent on regional meteorological factors including air temperature, relative humidity, solar radiation, and wind speed, as well as CWTS design features including plant species diversity and density (Allen et al., 1998).

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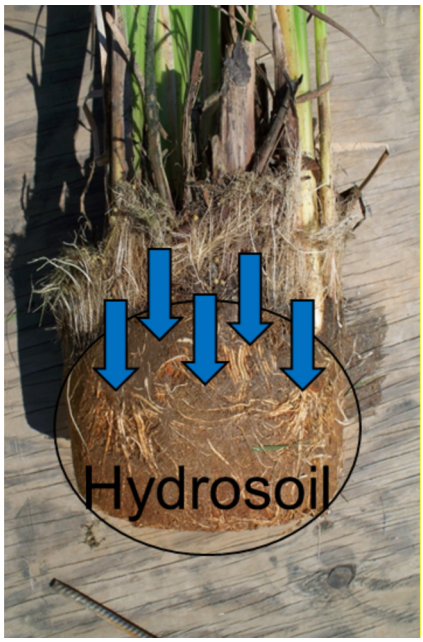

Fig. 1. Excavated *T. latifolia* with root mass showing root growth above the hydrosoil surface. Arrows indicate hypothesized flow path generated by plant transpiration.

Changes in volumetric flow attributed to evapotranspiration can alter CWTS treatment performance by removing water from the system (thus increasing hydraulic retention time) and increasing concentrations of dissolved constituents. Differences in evapotranspiration attributed to CWTS size, climatic region, and plant selection can lead to inaccurate predictions of treatment performance when using previously determined removal rate coefficients. Because removal performance data collected from small, pilot-scale CWTS studies may be applied to designing full-scale CWTSs in different climatic regions, the extent to which differing evapotranspiration can affect treatment is of interest.

Additionally, because both the inflow and outflow of free water surface (FWS) CWTSs are located above the hydrosoil, a decreasing hydraulic head with depth is needed to advectively transport targeted constituents to the hydrosoil where treatment by specific redox-driven reactions occurs (Kadlec, 1999; Kadlec and Wallace, 2009; Martin and Reddy, 1997; Martin et al., 2003). Previous studies suggest that plant transpiration plays a role in establishing a vertical hydraulic gradient within wetland hydrosoil (Martin et al., 2003). The extent to which constituents are transported advectively can be estimated through a transpiration to evapotranspiration ratio based on the assumption that water lost through plant transpiration must move through the root zone (Kadlec and Wallace, 2009). However, root density and location can affect flow through the hydrosoil and water column (Fig. 1). Therefore, the ability of plant transpiration to vertically transport constituents warrants investigation to determine if FWS CWTSs are capable of supporting treatment by redox-driven reactions in the hydrosoil.

The objectives of this paper are to (1) determine the crop coefficient for a small-stand, pilot-scale CWTS, (2) predict differences in constructed wetland treatment performance attributed to evapotranspiration-driven water loss, and (3) measure the effects of plant transpiration on vertical flow of constituents. Completion of these objectives provides a fundamental understanding of the effects of evapotranspiration on treatment performance in FWS CWTSs containing *T. latifolia*.

2. Materials and methods

2.1. Pilot-scale crop coefficients for Typha latifolia

T. latifolia evapotranspiration (ET_c) was monitored using four 0.5-m^2 containerized wetland troughs connected in series to form a 2-m^2 constant-head lysimeter with dimensions similar to pilot-scale CWTSs used in many previous studies (e.g. Dorman et al., 2009; Horner et al., 2012; Kanagy et al., 2008; Spacil et al., 2011). The lysimeter consisted of four 265-L troughs, each filled to a depth of 45 cm with sandy river sediment collected from nearby 18-mile Creek (Clemson, SC) and planted to field density (approximately 20 plants per trough or 10 plants per m^2) with *T. latifolia* collected from nearby aquaculture ponds. The four troughs were connected in series with 2.5-cm diameter polyvinyl chloride (PVC) piping and arranged for gravity flow, with fixed overflow pipes installed in each trough to maintain a constant head and water-depth of 15 cm (Fig. 2). Water was supplied to the first trough at a constant rate of 6 L h^{-1} (6×10^6 mm^3 h^{-1}) by a Fluid Metering Inc.® pump (QG400). The lysimeter was allowed to mature for approximately 3 years before any ET_c data were collected. The plants were fertilized periodically to promote vigorous growth. The lysimeter remained outdoors in Clemson, SC (34.69° N, 82.81° W) for the duration of the experiment from July through August 2011.

Volumetric outflow of the lysimeter was monitored using a RainWise® Inc. tipping bucket rain gauge placed under the outflow pipe of the last trough of the lysimeter (Fig. 2). The rain gauge was connected to a RainWise® RainLog digital data logger with 256 kB of non-volatile memory capable of recording flow information at a resolution of 1 min. The rain gauge was calibrated prior to the experiment using ten timed, 1-min intervals of a constant 6 L h^{-1} flow rate provided by the FMI QG400 pumps. Hourly volumetric outflow data were recorded and downloaded for three 5- to 7-day intervals in July and August after the plants had reached maturity.

ET_c (mm h^{-1}) was calculated as the difference between the volumetric inflow and outflow divided by the surface area of the lysimeter for data collected during dry periods with no precipitation (Eq. (1)).

$$ET_c = \frac{Q_{in} - Q_{out}}{SA} \quad (1)$$

where Q_{in} is volumetric inflow of the lysimeter (6×10^6 mm^3 h^{-1}), Q_{out}, is measured volumetric outflow of the lysimeter (mm^3 h^{-1}), and SA is measured surface area of the lysimeter (2×10^6 mm^2).

Small-stand crop coefficients for *T. latifolia* were determined using linear regressions of hourly ET_c measured from the lysimeter and hourly reference evapotranspiration (ET_o). ET_o values were calculated using the FAO-56 Penman-Monteith method (Allen et al., 1998; Penman, 1963) from meteorological data collected with an on-site Davis Instruments® Vantage Pro 2 weather station. The FAO-56 Penman–Monteith method (Eq. (2)) was used to calculate ET_o for a reference crop with an assumed crop height of 0.12 m, fixed surface resistance of 70 s m^{-1}, and albedo of 0.23. This method was selected because it meets the precision required for calculating crop coefficients using readily acquired meteorological data (e.g. temperature, dew point, wind speed, and solar radiation) and is commonly used in other evapotranspiration studies (e.g. Allen et al., 1998).

$$ET_0 = \frac{(0.408)\,\Delta\,(R_n) + \gamma \frac{37}{T+273} u_2\,(e_s - e_a)}{\Delta + \gamma(1 + 0.34\ u_2)} \quad (2)$$

where ET_o is reference evapotranspiration (mm h^{-1}) calculated from meteorological data; Δ is slope of the saturation vapor pressure temperature relationship (kPa °C^{-1}, 1 kPa = 1×10^3 pascals); R_n is measured net radiation (MJ m^{-2} h^{-1}, 1 MJ = 1×10^6 J); γ is