Evapotranspiration Crop Coefficients for Cattail and Bulrush

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Abstract: Accurate estimates of evapotranspiration from constructed wetlands are required to establish design flow estimates and to assess the effectiveness of wetland water quality amelioration. Water consumption by two wetland plant species, *Typha latifoilia* (broadleaf cattail) and *Scoenoplectus acutus* (hardstem bulrush), was measured in a greenhouse for eight months. Measurements of actual evapotranspiration (ET_C) from replicates of both plant treatments were related to potential evaporation (ET_0) as approximated by evaporation from saturated gravel beds. Ratios of ET_C to ET_0 were used to develop crop coefficients (K_c) for each plant species. The relationship between cattail ET_C/ET_0 and the ratio of vegetative to open water surface area (S_V/S_0) agreed with previous investigations. A linear relationship was used to account for advective energy fluxes due to peripheral canopy area. Cattail crop coefficients were scaled according to this relationship. The resulting scaled crop coefficient curve may be transferable to constructed wetlands of a known S_V/S_0.

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Introduction

Accurate estimates of evapotranspiration from constructed wetlands are required to establish design flow estimates and to assess the effectiveness of wetland water quality amelioration. Evapotranspiration is defined as the total flux of water from a surface due to the combined effect of evaporation and transpiration of plants. Potential evapotranspiration (ET_0) is the evapotranspirative flux in a nonlimiting system. ET_0 can be calibrated to evaporation from a large open water body or evapotranspiration from an extensive land surface covered in an actively growing reference plant (Doorenbos and Pruit 1977). Crop coefficients account for the difference between evapotranspiration from a cropped surface and potential evapotranspiration (Burman 1980; Allen et al. 2001):

$$ET_C = K_c ET_0 \tag{1}$$

where ET_C = crop evapotranspiration (mm/day); ET_0 = potential evapotranspiration (mm/day); and K_c = dimensionless crop-specific coefficient. Crop coefficients account for specific plant physiology and are developed by measuring ET_C in a field setting, predicting ET_0, and calculating the ratio of the two over common time intervals. The attractiveness of this approach is the transferability of the crop coefficients.

Many energy-based ET_0 models are built upon the assumption that a uniform flux of advective energy occurs over an essentially infinite, one-dimensional canopy. However, canopies of isolated stands are highly three dimensional. Failure to account for the effect of the advective exchange across the additional peripheral area can result in unrealistically high ET_C/ET_0 ratios and thus limit the transferability of these crop coefficients to wetlands of more complex geometry.

Efforts have been made to resolve the effect of advective loss due to canopy geometry. Allen et al. (2001) provides a method for estimating K_c based on the width of the vegetation stand and a measure of relative availability of water in the area surrounding the stand. The utility of this approach, however, is limited for stand widths less than 10 m. Anderson and Idso (1987) accounted for the increased advection on isolated stands, also known as the clothesline effect, by normalizing peripheral surface area of the plant canopies against the open water surface area for tanks of similar diameters. Subsequently, Idso and Anderson (1988) found a linear relationship between cattail ET_C/ET_0 ratios and the ratio of canopy surface area to open water area (S_V/S_0) in a new analysis of data reported by Snyder and Boyd (1987). The data were synthesized and a linear equation for this regression was later reported by Allen et al. (1996) as

$$ET_C/ET_0 = 0.54(S_V/S_0) + 0.22 \tag{2}$$

where S_V = vegetative surface area; and S_0 = open water surface area.

In the current study, ET_C was measured in a controlled greenhouse environment over one growing season in monoculture treatments of *Typha latifoilia* (broadleaf cattail), *Scoenoplectus acutus* (hard-stem bulrush), and control gravel beds. ET_C/ET_0 ratios, using gravel bed evaporation as potential evapotranspiration, were computed for both species. Finally, a seasonally vary-

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ing crop coefficient for broadleaf cattail was developed by scaling the ET_C/ET_0 ratios to area ratios according to Eq. (2).

Methods and Materials

Six constructed wetland cells that have been used to study wastewater treatment efficacy (Stein et al. 2002) in an environmentally controlled greenhouse in Montana State University's Plant Growth Center were instrumented for measurement of evapotranspiration. Each cell is 152 cm long, 76 cm wide, and 53 cm deep, constructed of 1.3 cm polypropylene sheeting, and filled with 13–19 mm diameter gravel to a depth of 47 cm. In a repeating process, float switches and clock-driven solenoid valves filled reservoirs during 15 min periods, then drained them into the wetland cells. Thus, a pseudocontinuous flow rate of 30 ml/min was delivered. A detailed description of this water delivery system is given by Borden (2001). Outflow from the cells was measured using a custom-made dosing flush meter (Towler 1999). Operation of these meters involved the periodic flush of a known volume at recorded time intervals to measure the time-averaged flow rate. Flush volumes were approximately 900 ml and time intervals ranged from 30 min to 2 h in response to diurnal variations in water consumption. Two cells each were planted with cattail and bulrush in December 1995, while two cells were left as unplanted controls. Detailed plant growth characterization was conducted on all cells during the third growing season (Towler 1999) and detailed water balance measurements were conducted during the sixth growing season (3/30/01–11/16/01). Due to the seasonal temperature cycling in the greenhouse, the plants followed seasonal patterns of growth, maturation, and dormancy during the study period.

The greenhouse temperature setting was varied between 16 and 24°C by 4°C increments at approximately 2 month intervals beginning in mid-April. Incoming solar radiation, temperature, and relative humidity were measured at 3 m above the gravel surface near the center of the greenhouse using a radiometer, thermocouple, and a relative humidity sensor, respectively. Additional thermocouples were installed in the front-left quadrant of each wetland cell to measure soil temperatures. Similarly, three plant canopy air temperature measurements for each cell were recorded by thermocouples placed at 0, 1, and 2 m heights above the gravel. Canopy height measurements were taken coincident with the first evidence of new shoot growth on 3/30/01, and subsequent measurements were made every six weeks. Estimates of green leaf area indices (LAI_G) were made based on the relationship between LAI_G and canopy height established in 1998. Canopy surface areas (S_V), the surface of the projection of the basal area through the canopy height, were measured every 6 weeks. Evapotranspiration, measured as the difference between measured inflow and outflow, was recorded daily during the entire growing season beginning in early March and ending in late November. The water level in all cells was maintained within 1 cm of the gravel surface throughout the experiment. Any minor self-mulching effects were offset by slight contributions of the wetted gravel to the effective evaporative surface area. This allowed for the control treatment to be used as a measure of potential evapotranspiration (ET_0).

Results

Greenhouse environmental variables measured during the 2001 growing season are shown in Fig. 1. Daily averages of water flux for the planted and control treatments, defined as ET_C and ET_0, respectively, are reported in Fig. 2. Differences between replicates of the same treatment were not significant at the 99.99% confidence interval, suggesting that minor variations of microclimate within the greenhouse had no significant effect on water consumption. Mean daily evaporation from the saturated gravel bed cells exhibited little seasonal variation as compared with mean evapotranspiration from the cattail and bulrush cells. Early in the growing season, the unplanted control treatment had evaporation rates near the observed ET_C from both planted treatments. Thereafter, both planted treatments had ET_C rates consistently greater than the control evaporation rate. A two-sample t-test, assuming unequal variances, was performed on the ET_C data sets for each treatment. The mean ET_C values for bulrush and cattail were statistically different at a confidence level in excess of 99.99%. Both cattail and bulrush cells displayed a clear seasonal trend in ET_C, peaking in late August. Peak bulrush ET_C occurred later than peak cattail ET_C and was lower in magnitude when compared with peak cattail ET_C. Relative to the increase in ET_C rate, the decline in ET_C rate for both species was rapid once the peak was reached. The measurements of the overall seasonal ET_C are reported in Table 1.

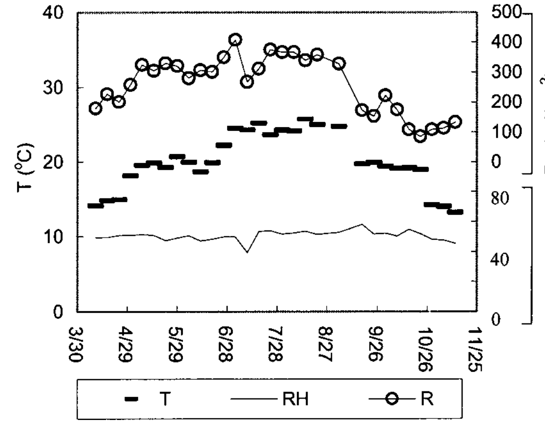

Fig. 1. Seven-day averages of air temperature (T), net solar radiation (R_n) and relative humidity (RH)

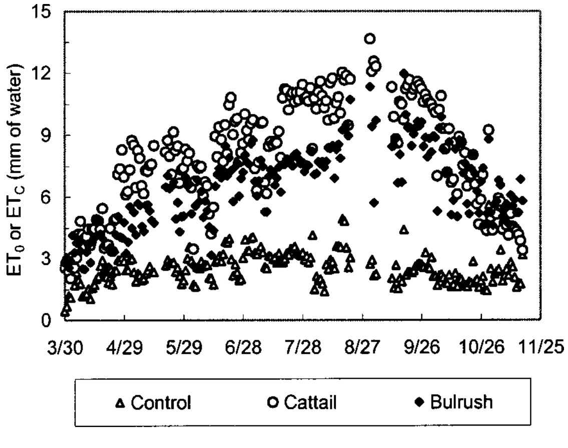

Fig. 2. Mean daily evaporation (ET_0) from saturated gravel beds and evapotranspiration (ET_C) from cattail and bulrush treatments

Table 1. Descriptive Measurements of Seasonal Evapotranspiration for All Three Treatments

Cell (s)	Treatment	Mean (mm)	Median (mm)	Maximum (mm)
3	Control	2.41	2.35	7.09
8	Control	2.55	2.60	5.79
4	Cattail	7.87	8.34	13.58
6	Cattail	8.04	7.89	14.08
7	Bulrush	6.60	6.98	12.21
5	Bulrush	6.25	6.27	11.96
3,8	Control	2.48	2.42	5.60
4,6	Cattail	7.96	8.14	13.63
5,7	Bulrush	6.43	6.76	11.96

Discussion

Evapotranspiration measurements began with the evidence of new shoot growth in late March of 2001. As such, the initial ratios of ET_C/ET_0 should have been unity, because transpiration was negligible. However, both planted treatments had ratios greater than 1.0 at the start of the growing season (Fig. 4). The plant stalks that remained after harvesting likely contributed to these high initial ET_C rates in two ways. First, though dead or dormant, the 5 cm stalks were wetted by a capillary effect. These wetted leaves, oriented in discrete stalks as opposed to a complete canopy, provided more evaporative surface area than would be accounted for using this method of measuring S_V. Second, the measurements of new growth were recorded once leaves grew out of the existing dead plant matter. Thus, these shoots were already 5 cm in height and, in terms of their effect on advective energy contributions to ET_C, geometrically significant. Despite this, the effect on the overall seasonal ET_C/ET_0 trend was minor.

Because gravel bed evaporation displayed minimal seasonal variation, ET_C/ET_0 closely tracks planted treatment ET_C; the cattail treatment reached a maximum value in late August while the bulrush treatment peaked in late September, suggesting that cattail matures more quickly and starts dormancy earlier under these environmental conditions.

Specific Crop Coefficients for Broadleaf Cattail and Hardstem Bulrush

Seasonal crop coefficient (K_c) curves for broad-leaf cattail and hard-stem bulrush were developed. Using the method outlined in Allen et al. (2001) for single crop coefficients, the seasonal variability of K_c was partitioned into four discrete subseasons defined by specific plant indicators. In this experiment, LAI_G and canopy height measurements were used in lieu of Allen's indicators, which are more appropriate to agronomic crops. The onset of rapid plant growth was used to separate the initial stage from the plant development stage. This development occurred in early July for cattail and late July for the bulrush treatment. The plant development stage continued until a fully green, mature canopy cover was reached. LAI_G values peaked during early and late August for cattail and bulrush, respectively. The boundary between midseason and late season stages was identified by a discoloration in the plants and a decrease in LAI_G. Once the curves were partitioned into these four stages, the values of K_c within each stage were calculated. A residual was defined as the difference between the $ET_C//ET_0$ measurement recorded at each 7 day observation and the value of K_c predicted by the curve. The optimal K_c within each stage was then determined by minimizing the mean squared residuals for each stage. The specific crop coefficient curves in Fig. 4 are based on the canopy in this study, and, as such, these coefficients may not be appropriate for use with stands of different geometry.

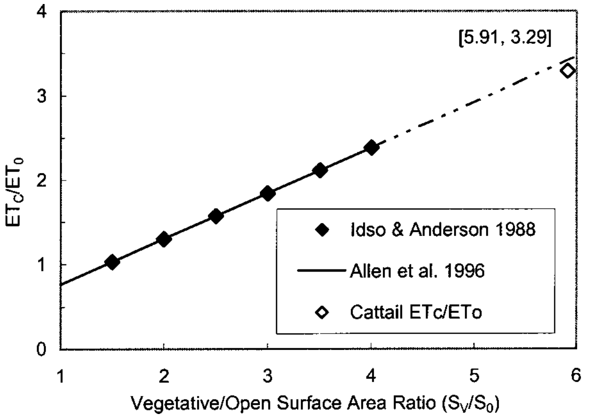

Fig. 3. Extrapolating linear regression equation developed by Allen et al. (1996) and Idso and Anderson (1988) to include $[S_V/S_0, ET_C/ET_0]$ pair developed in this study

Transferable Crop Coefficient for Broadleaf Cattail

The mean seasonal cattail ET_C/ET_0 ratio (3.29) was larger than most of the values reported by Allen et al. (1996). However, as compared with the investigations summarized in that paper, the basal area of cells in this study was small and the peripheral canopy area was large. Thus, it was not surprising that the mean seasonal S_V/S_0 ratio (5.91) represented an upper extreme. Given this canopy geometry, advection due to the clothesline effect clearly played a dominant role in evapotranspiration. Seeking to account for the effects of advective loss, this $[S_V/S_0, ET_C/ET_0]$ pair was compared with the linear equation reported by Allen et al. (1996) (Fig. 3). The observed $[S_V/S_0, ET_C/ET_0]$ pair of [5.91,3.29] agreed closely with the value of [5.91,3.41] predicted by Eq. (2). That suggested that this method of accounting for the effects of additional advective losses due to high peripheral surface area is valid to at least a S_V/S_0 of 5.91.

Using Eq. (2), the cattail crop coefficient curve in Fig. 4 was proportionally scaled from an observed S_V/S_0 of 5.91 down to

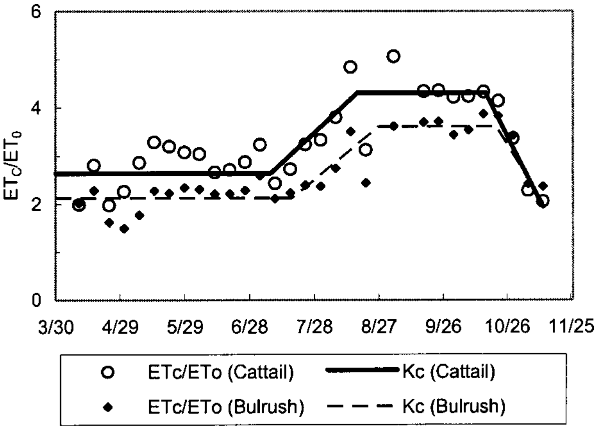

Fig. 4. Seven-day averages of ET_C/ET_0 and crop coefficient curves (K_c) for cattail and bulrush treatments

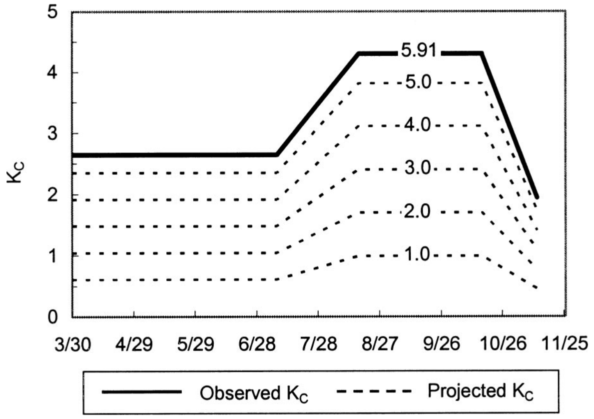

Fig. 5. Scaled crop coefficient (K_c) curves for broadleaf cattail; values at curve peaks represent ratio S_V/S_0

1.0, the surface area ratio representing an infinite expanse of cattail. In doing so, a family of crop coefficient curves (Fig. 5) was generated for stands of varying S_V/S_0 ratios. Note that, for the curve representing an S_V/S_0 ratio of 1.0, the peak K_c value is similar to ET_C/ET_0 values reported by large field-scale water balance studies (Eisenlohr 1972; Brown 1981; Heimburg 1984). This agreement with an independently observed lower extreme of S_V/S_0 further validates this approach to adjusting the coefficient for advective losses and justifies a high degree of transferability.

Application to Evapotranspiration Prediction

This family of crop coefficient curves for broadleaf cattail may be transferable to the prediction of ET as part of constructed wetland design water budget. Predictions of cattail ET using these curves may be performed in the following steps: (1) measure the ratio of vegetative surface area to basal area (S_V/S_0); (2) determine the cattail crop coefficient based on this ratio and stage of the growing season; (3) calculate actual cattail ET using an appropriate measure of potential ET, the crop coefficient, and Eq. (1). It is important to reiterate the restrictions on the application of this approach. The wetland should have the appropriate canopy geometry, as defined by an S_V/S_0 ratio in the range of 1.0 to 5.91. Furthermore, the stand in question must be actively growing and not be water limited. Finally, it is important that the practitioner recognize the conditions under which this approach was developed. Applying these crop coefficients to drastically different situations may limit their accuracy.

Conclusions

Results of this study demonstrated a relationship between environmental factors and evapotranspiration for two constructed wetland plant species, cattail and bulrush. Both species consistently exhibited higher ET_C rates than the unplanted control ET_0, and cattail replicates consistently recorded higher water losses than the bulrush replicates. This supported the argument that vegetation type is a strong factor in determining wetland evapotranspiration.

ET_C/ET_0 ratios and plant growth status measurements were used to develop crop coefficient curves for both vegetation types. The development of these curves was based on the methods presented by Allen et al. (2001). These coefficient curves are linked to the canopy geometry in this experimental design and, thus, are unadjusted for the effects of advection. While useful in demonstrating the effect of vegetation type on wetland evapotranspiration rates, due to the interplay between canopy shape and advective loss, these specific curves may be limited in their transferability.

A transferable crop coefficient curve for broadleaf cattail was developed by accounting for the effects of advection. Building upon work performed in previous investigations, the coefficient for cattail was adjusted for variations in S_V/S_0 ratios. This approach allows for the prediction of cattail ET_C for varying degrees of peripheral canopy surface area and may prove useful to the practitioner in estimating cattail evapotranspiration.

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