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Estimation of evapotranspiration by reed canarygrass using field observations and model simulations

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Summary Reed canarygrass (*Phalaris arundinacea*) commonly invades meadow wetlands, effectively dominating water use and outcompeting native plants. Objectives of this study were to (i) estimate daily, seasonal and annual water use by reed canarygrass using shallow water table fluctuations; and (ii) calibrate the ALMANAC (Agricultural Land Management Alternative with Numerical Assessment Criteria) model to accurately simulate water uptake by this grass. Using a groundwater well, the water table under an area in Iowa dominated by reed canarygrass was monitored hourly. Differences between water level measurements taken each hour were averaged to determine the hourly water table change in each month. Using these estimates of water use, the ALMANAC model was then calibrated to simulate plant transpiration values close to these water table use rates. Average monthly calculated daily plant water use rates were 3.3 mm d^{-1} in July and 2.3–2.8 mm d^{-1} in May, June, August, and September. Simulated bimonthly values for measured water use and plant transpiration simulated by the ALMANAC model differed by 14% or less. From May to October the mean ratio of measured to simulated values was 94%. Thus, the similarity between simulated plant transpiration and water use from the water table showed promise that this process-based model can realistically simulate water use under such grassland systems.

Introduction

Reed canarygrass (RC) is a common perennial grass in the humid areas of northern United States and southern Canada (Galatowitsch et al., 1999). The tall (60–150 cm) circumboreal grass is considered among the most invasive species found in wetlands, along streambanks and in lowland areas (Wetzel and van der Valk, 1998; Galatowitsch et al., 1999; Zedler and Kercher, 2004). RC has been cultivated as forage grass and for erosion control because it is adapted to wide extremes in soil moisture and nutrients (Hitchcock, 1950; Wetzel and van der Valk, 1998; Galatowitsch et al., 1999;

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Kercher and Zedler, 2004). It thrives in areas with high annual or periodic fluctuations in water levels and is considered among the most productive cool season grasses during drought (Galatowitsch et al., 1999). Wetzel and van der Valk (1998) observed that the morphological characteristics of *Phalaris arundinacea* (rapid growth rate, tall, leafy shoots and lateral spread of the canopy and ramets) enabled the plant to maximize growth even under low nutrient and soil moisture conditions. Because of its competitive advantages, the grass often forms monotypes, making restoration of sedge meadow wetlands difficult (Perry and Galatowitsch, 2003, 2004).

On a landscape scale, RC dominates many riparian corridors of agricultural and urban watersheds where variable hydrologic conditions are found (Kercher and Zedler, 2004). Because evapotranspiration (ET) is often a significant component of the water budget in riparian ecosystems (Loheide et al., 2005), an accurate estimate of water uptake by RC is thereby needed to assess the effects of the cool-season grass on the basin-scale water cycle. However, few studies have reported water use rates from RC. Mueller et al. (2005) used lysimeter and field experiments to estimate that RC consumed approximately 400–900 mm, or approximately 2.2–4.9 mm d^{-1}, of groundwater from April to September near Berlin, Germany. In Iowa, Zhang and Schilling (2006) used a water table recession model to estimate that water use by RC averaged 2.8 mm d^{-1} during a 33-day period in July and August. They suggested that the amount of water use by the grass decreased exponentially with depth from 7.6 mm d^{-1} to zero as the water table declined from the ground surface to 1.42 m below ground surface.

Recently, Schilling (2007) used water table fluctuations to estimate water use from three riparian land covers including RC. Plant water use was estimated by multiplying the change in water table level from 1 h to the next (L/T) by the estimated specific yield of the aquifer (dimensionless), and then summing the hourly water use estimates each day. Plant water demand of RC was estimated to range from 1.5 to 3.1 mm d^{-1} from July to September using this method. Diurnal water table fluctuations have been used by others to estimate plant water use, especially in arid or semi-arid regions (e.g., White, 1932; Robinson, 1958; Van Hylckama, 1970; Nagler et al., 2003; Loheide et al., 2005) or in wetland studies (Rosenberry and Winter, 1997; Gerla, 1992; Lott and Hunt, 2001). Schilling (2007) observed that water table fluctuations under RC showed a stepped pattern of water level declines rather than the commonly observed diurnal pattern of rising and falling water levels. Water table declines were greater during peak plant water demand in the day compared with a slow rate of decline during the nighttime hours.

In this study, shallow water table fluctuations were used to estimate water uses rates from RC during a May to December period in Iowa. The July to December period previously analyzed by Schilling (2007) was included in this paper, as well as data for May and June, thereby extending the time period to the entire growing season for RC. The water use estimates derived from field observations were used to calibrate the ALMANAC (Agricultural Land Management Alternative with Numerical Assessment Criteria) model for use in simulating water use by RC.

The objectives of this paper were to (i) estimate daily, seasonal and annual water use by RC using shallow water table fluctuations; and (ii) calibrate the ALMANAC model so that it accurately simulated water uptake by RC. Combining field monitoring with numerical modeling in this study played to the strengths of both methods to estimate plant water uptake. While results from field monitoring alone may be prone to uncertainties, numerical modeling, given soil, climate and plant parameters, can simulate water use rates when combined with field data for calibration. This study provided much needed information on water use rates from a cool season grass that is commonly found in the riparian corridors of watersheds. Estimated water use rates for RC can then be incorporated into watershed models to better capture vegetation water losses in the water budget of a watershed.

Methods

Field observations

The study area is located in the central portion of the Walnut Creek watershed at the Neal Smith National Wildlife Refuge (NSNWR) in Jasper County, Iowa, USA (Fig. 1). In July 2003, a shallow well (2 m) was installed in the riparian zone of Walnut Creek densely covered with RC (Zhang and Schilling, 2006). The well was positioned 40 m from Walnut Creek to minimize any effect that channel incision and possible surface–groundwater interaction would have had on riparian water table levels (Schilling et al., 2004). The well was installed using a 152-mm hand auger with a 50.8 mm diameter, 1.5 m long PVC screen and 0.61 m PVC riser. The annular space was backfilled with sand to a depth of 0.2 m and granular bentonite was placed around the well casing at the land surface to seal the well casing from surface impacts. Soil consisted of dark gray silty clay loam (2.5YR3/0, 10YR3/1-4/1).

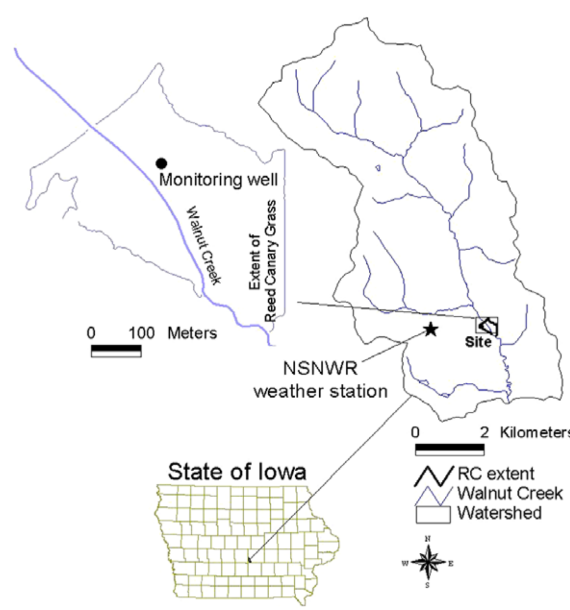

Figure 1 Location of study site.

The water table was monitored at 60-min intervals for 215 days from May 1 to December 1, 2004. A total of 5137 water level readings were obtained using an In situ mini-TROLL transducer (with vented cable) and data logger system. Accuracy of the transducer was within 1 mm. Precipitation during the study period was monitored at hourly intervals at a weather station located at the Prairie Learning Center of the Neal Smith National Wildlife Refuge (NSNWR) (Fig. 1).

Water table fluctuations were examined in detail by evaluating hourly water table behavior on a daily and seasonal basis. Time periods were broken into months to assess differences in ET rates across a growing season. Because the shallow water table responded rapidly to rainfall events and occasionally resulted in ponded water above the land surface, a brief period following intense rainfall periods was not considered in the analysis. The water level fluctuation was not evaluated until the water table dropped below the land surface. The difference between water level measurements taken each hour was measured and then averaged across the monitoring period to determine the hourly water table change in each month.

Specific yield (Sy) is defined as the volume of water released under gravity from storage per unit cross-sectional area per unit decline in water table (Freeze and Cherry, 1979). In this study, Sy was estimated from the ratio of water table rise to total rainfall (Timlin et al., 2003; Healy and Cook, 2002; Risser et al., 2005; Loheide et al., 2005). Loheide et al. (2005) recommended that this method apply to sites with a shallow water table and high soil water content, both conditions that were met by the study site. Estimates of Sy were used to convert water table fluctuations under the riparian land covers to plant water demand from plant water use, i.e.

$$\text{Plant water use} = \sum (d_i - d_{i-1}) \times \text{Sy} \tag{1}$$

where plant water use is average daily plant water use rate in mm d^{-1} for the monitoring period, d_i and d_{i-1} are the observed depth to water table on hour $i-1$ and hour i, respectively, and Sy is specific yield. For the monitoring periods, the hourly water table difference was multiplied by the Sy to obtain an hourly plant water use rate. The hourly plant water use rates for each hour of the day were averaged to obtain an hourly pattern of plant water demand for each day and month.

Model simulations

A grassland model useful for diverse soils and diverse climates needs sufficient detail for simulating differences among grass species, soils and climate conditions without prohibitively large input requirements. ALMANAC is a process-based simulator of plant communities. It simulates plant growth with sufficient detail to be easily transferable among regions without recalibration. ALMANAC contains subroutines and functions from the EPIC model (Williams et al., 1984), with additional details for plant growth. Parameters describing growth of several grasses species have been developed from field experiments (Kiniry et al., 1999, 2007). Parameters for other plant species can often be derived from the literature.

The ALMANAC model is a valuable tool for cropping systems (Debaeke et al., 1997; Kiniry and Bockholt, 1998; Xie et al., 2001), for Alamo switchgrass (*Panicum virgatum* L.) (Kiniry et al., 1996, 2005), and for rangelands and improved grass pastures (Kiniry et al., 2002, 2007). The model simulates the processes of plant growth and soil water balance including light interception by leaves, dry matter production, and partitioning of biomass into seeds. It simulates daily plant growth through leaf area index (LAI), light interception, and a constant for converting intercepted light into biomass (radiation-use efficiency). Stresses such as nutrient deficiency, drought, or temperature extremes reduce LAI and biomass growth. The ALMANAC version used for this study has improved sensitivity to stomatal conductance, and has the water table simulation components described for the EPIC 9200 version used for saltcedar (*Tamarix*) simulation (Kiniry et al., 2003).

Critical water use in water-limited conditions was the simulated water demand. Potential evaporation (E_0) (Priestly–Taylor equation (Priestly and Taylor, 1972), for this study) was calculated first, and then potential soil water evaporation (E_S) and potential plant water transpiration (E_P) were derived from potential evaporation and leaf area index (LAI). Based on the soil water supply and crop water demand, the water stress factor was estimated to decrease daily crop growth and yield. E_S and E_P were estimated by:

$$E_P = E_0(\text{LAI}/3) \quad 0 \leqslant \text{LAI} \leqslant 3.0 \tag{2}$$
$$E_P = E_0 \quad \text{LAI} > 3.0 \tag{3}$$

E_S is either $E_0 \exp(-0.1\text{BIO})$ or $E_0 - E_P$, whichever was smallest, where BIO was the sum of the above ground biomass and crop residue (Mg ha^{-1}):

$$E_S = E_0(1 - 0.43\text{LAI}) \quad 0 \leqslant \text{LAI} \leqslant 1.0 \tag{4}$$
$$E_S = E_0 \exp(-0.4\text{LAI})/1.1 \quad \text{LAI} > 1.0 \tag{5}$$

Water stress factor (WSF) was the ratio of water use to water demand calculated from potential plant transpiration in the model, and water use (WU) was a function of plant extractable water and root depth. If available water in the current rooting zone was sufficient to meet demand, then WU equaled E_P. Otherwise, WU was restricted to the water available in the current rooting zone. The simulations used soil parameters for an Otley silty clay (fine, smectitic, mesic Oxyaquic Argiudolls) that is 1.85 m deep, with a runoff curve number of 73.

Plant parameters for reed canarygrass were derived from values for this and similar species and not used for fitting the model to the measured water use estimates. For radiation use efficiency, we used 3.5 g MJ^{-1} intercepted photosynthetically active radiation, similar to some values for native grasses (Kiniry et al., 1999). The values for potential leaf area index (LAI) and degree days were based on RC values from Finland (Sahramaa, 2004). The maximum potential LAI value was 5.0. Anthesis occurred when 50% of degree days to maturity had accumulated. There were 2880 degree days to maturity each year (base temperature of 3 °C and optimum temperature of 25 °C), based on the accumulated degree days until the middle of October. The parameters that defined leaf area development specified that plants reach 17% of potential LAI when 5% of the degree days had accumulated and 90% of potential LAI when 40% of the degree days had accumulated. Late in the season, leaf area senescence was simulated with a slow rate of decrease from the day that 50% of seasonal degree days had accumulated until date of maturity (RLAD = 0.1). We used a value of 0.2 m for the maximum rooting depth possible for RC (Comes et al., 1981). We assumed the water table depth could fluctuate between 0.01 and 1.42 m during each season, as described below.

Model output that was used included both the total monthly ET and the total monthly plant transpiration (EP).

Results

Field observations

A total of 669 mm of precipitation occurred during the 215-day monitoring period (Fig. 2). May, July and August were the wettest months with total monthly precipitation of 177, 136 and 167 mm, respectively. Major rainfall events that occurred on May 17 (40 mm), May 24 (33 mm), July 10–11 (40 mm), July 22 (26 mm), August 3–4 (80 mm) and August 25–28 (101 mm) accounted for nearly 48% of the total precipitation falling during the study period. Overall, total rainfall in 2004 measured in Walnut Creek watershed (807 mm) was similar to the long-term average for central Iowa (849 mm) (Schilling et al., 2006) and suggests that climate conditions during this study were representative of typical central Iowa conditions.

The water table depth under RC in the riparian zone of Walnut Creek varied from ponded conditions to 1.42 m below ground surface and averaged 0.73 m (Fig. 2). The hydrograph was characterized by several rapid water table rises following rainfall events followed by extended periods of water table declines. At least 12 groundwater recharge events were observed during the May to October period (Fig. 2). As observed previously, a stepped pattern of water table fluctuation was typically observed, with greater water table declines during the day than during the night. This was

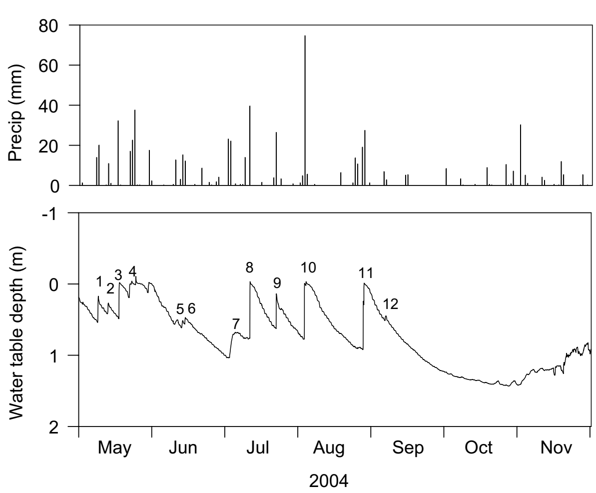

Figure 2 Hydrograph of hourly water table depth measurements for the May 1 to December 1, 2004 period. Daily precipitation data from the Prairie Learning Center at the Neal Smith National Wildlife Refuge.

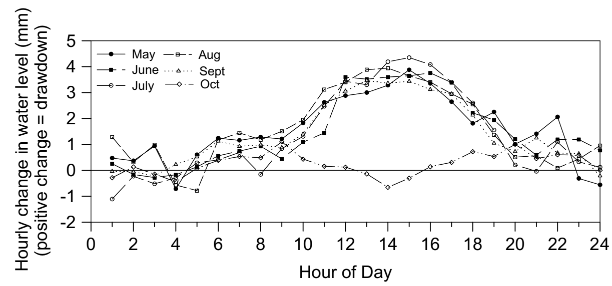

Figure 3 Summary of water level change from 1 h to the next for the May to October monitoring period.

particularly evident in the hourly water table fluctuations (Fig. 3). Beginning around 0800, water levels declined to a maximum rate of 4 mm h^{-1} from 1400 to 1600 then decreased to 1 mm h^{-1} from 2000 to 0800 (Fig. 3). The mm h^{-1} rate of change was within the margin of error for the transducer, suggesting that water uptake by RC was negligible during the nighttime hours. The hourly pattern of water level declines was similar for the months of May through September but was notably flat during October. This suggested that RC was no longer using measurable quantities of groundwater in October following plant senescence.

The rapid rise in the water table during rainfall events was used to estimate the specific yield of the aquifer, as described above. From the 12 recharge events noted in Fig. 2, the amount of water table rise relative to the rainfall depth was evaluated to estimate the specific yield of the aquifer (Table 1). The specific yield ranged from 0.027 to 0.157 and averaged approximately 0.083. Average monthly specific yield values were similar in May and July (0.07) and August (0.045), and slightly higher in June (0.14) and early September (0.105). Higher specific yield values in June and September may imply that soil moisture reserves were more depleted during these months with unsaturated soils capturing more infiltrating precipitation. However, these months were also characterized by lower rainfall depths than other months (Table 1).

Specific yield is known to vary with water table depth (Schilling, 2007; Sophocleous, 1985; Duke, 1972), but the relation of specific yield to water table depth at the site was not significant ($P > 0.1$). Perhaps the relatively narrow range of water table depths considered in this study (0.8 m) and the presence of a high water table in the riparian zone reduced the significance of the relation. The amount of capillary rise in the silt loam soils along Walnut Creek may be on the order of 1–2 m (Gillham, 1984) and likely plays an important role in maintaining high soil moisture levels in riparian soils.

The hourly water level declines (Fig. 3) were multiplied by the average specific yield (0.08) to estimate daily and seasonal water use by RC (Table 2). Daily water use was summarized for a 12-h ''growing day'' (8:00–20:00) to assess the plant water use occurring during daylight hours when RC was actively transpiring. Although the fixed 12-h period did not reflect variations in daylight length that occur throughout the growing season, the 12-h value was consistent with daily water level patterns that showed most of the water table decline occurring during this time interval (Fig. 3). In contrast, relatively minor water table fluctuations were

Table 1 Estimated specific yield from relation of water table rise to rainfall depth

Peak no.	Date	Precip (mm)	Water level rise (mm)	Water table depth (m)	Estimated specific yield	Monthly average Sy
1	May 9	34	372	0.542	0.091	
2	May 13	43	152	0.419	0.072	
3	May 17	32	507	0.488	0.063	
4	May 22	19	193	0.193	0.088	0.078
5	June 12	15	98	0.611	0.157	
6	June 14	9.5	12	0.564	0.127	0.142
7	July 3	45	337	1.038	0.125	
8	July 11	40	795	0.762	0.050	
9	July 22	26	490	0.626	0.054	0.076
10	August 3	50	783	0.774	0.063	
11	August 27	19	681	0.922	0.027	0.045
12	September 6	6.8	65	0.512	0.105	0.105

Peak numbers refers to Fig. 2.

Table 2 Estimated daily and monthly plant water use from RC from hourly water table fluctuations measured during daytime from 8:00 to 20:00

Month	Total daily (mm)	Total monthly (mm)
May	2.5 ± 1.6	77
June	2.8 ± 1.3	84
July	3.3 ± 1.8	103
August	2.6 ± 1.5	81
September	2.3 ± 1.2	70
October	0.4 ± 0.7	13
Total		428

observed during the nighttime hours (21:00–7:00) when RC was not transpiring. Water table declines observed during nighttime hours probably represented the amount of water drained from the aquifer due to lateral flow to Walnut Creek.

Estimated daily plant water use rates were greatest in July (3.3 mm d^{-1}) and similar in May, June, July, and September (2.3–2.8 mm d^{-1}) (Table 2). Little plant water use was evident in October (0.4 mm d^{-1}) when water use during the day was essentially the same as during the night. Total water use by RC for the months of May to October was estimated to be 428 mm, or approximately 2.3 mm d^{-1} for the entire growing season. Without including October, the average daily plant water use for RC was 415 mm or 2.7 mm d^{-1}.

Model simulations

Monthly ratios of measured water use and simulated EP ranged from 0.73 to 1.16 and averaged 0.94 for the six-month period (Table 3). When aggregated on a longer bimonthly basis, values for measured water use and simulated EP in July and August were near 1. For the first two months (May/June) the average measured water use values were 86% of the average simulated EP, whereas in September/October, the average was 106% of measured. Hence, the model simulated EP may slightly overestimate RC water use in the early to mid-growing season (May and June), and underestimate plant water use in September, but the simulated EP appears to match field estimated plant water use very well in the mid-growing season of July and August. In October, both simulated EP and measured values indicated substantially less water use, with simulated EP slightly higher (18.2 mm) than measured water use (13.3 mm).

Table 3 Comparison of simulated ET, simulated EP, and measured water use based on water table fluctuations, all in mm of water per month, the simulated leaf area index (LAI) at the end of each month, and the simulated water table depth at the end of each month

Month	May	June	July	August	September	October
Simulated ET	158	157	171	128	84	48
Simulated EP	82	106	99	83	61	18
Measured water use	77	84	103	81	70	13
Measured/simulated ET	0.49	0.54	0.60	0.63	0.84	0.28
Measured/simulated EP	0.94	0.79	1.04	0.97	1.16	0.73
Bimonthly measured/simulated EP	0.86		1.01		1.06	
Simulated LAI	1.87	2.18	2.30	2.28	2.24	0.02
Simulated water table	0.10	1.42	1.42	0.13	1.42	0.10

Overall mean measured/EP was 0.94 and mean measured/ET was 0.56.

The values of simulated ET and measured water use showed greater deviations than for EP. The mean for all months for the ratio of measured water use/EP was 0.57. Monthly values varied from 0.28 to 0.84 for this ratio. We assumed that EP was driving the water use from the water table. Thus, the similarity between EP and water use from the water table was encouraging.

Discussion

Field observations suggest that water use for RC during the growing season from May to September was approximately 415 mm. Early in the growing season, our water level monitoring did not include the month of April although other studies indicate that RC begins to initiate growth early in the spring (Maurer and Zedler, 2002; Lindig-Cisneros and Zedler, 2002). If we assume that April plant water use by RC is similar to May, the total seasonal plant water use would be on the order of ∼500 mm from April to October. This value was within the range of estimated ET values (400–900 mm) determined by Mueller et al. (2005) using plot scale groundwater lysimeters. Since plant growth conditions were optimized in the Mueller et al. (2005) study, our results suggest that perhaps the lower range of the experimental data (∼400–500 mm) was more indicative of actual plant water use by RC in field settings typified by a fluctuating water table in silty clay loam soils. The estimated daily plant water use reported for a July and August period in this study (3.3–2.6 mm d^{-1}) was consistent with previous work by Zhang and Schilling (2006) who reported an average value of 2.8 mm d^{-1} for a similar period. However, a linear decrease of ET with water table depth reported by Zhang and Schilling (2006) was not observed in this study. In this study, water use by RC remained fairly constant through the growing season and did not vary appreciably despite water table depths fluctuating as much as 1.42 m. In contrast to the methods used in this study, Zhang and Schilling (2006) used an indirect measure of ET based on the difference in water table recession that occurred between one riparian zone consisting of RC and another one consisting of bare soil. Hence, the difference in ET characteristics likely stemmed from utilizing different methods of assessment and indicates the challenges involved with estimating ET at daily time steps using water table fluctuations. Nonetheless, seasonal water use behavior by RC derived from this study was consistent with other studies that reported high biomass production throughout an extended growing season (Galatowitsch et al., 1999; Mueller et al., 2005).

However, obtaining a true value for daily and monthly plant water use from RC was difficult using field monitoring methods. In particular, our greatest source of error in the field monitoring was obtaining a suitable estimate of specific yield. While using rainfall depth-water level rise to estimate Sy was an appropriate method based on site conditions, the estimated Sy did vary throughout the season. If the greater apparent Sy in June (0.14) was used to estimate plant water use in this month (rather than the average of all months), the estimated plant water use for June would have been approximately 4.3 mm d^{-1}, or 129.6 mm $month^{-1}$, nearly 50% higher than the estimate derived from a constant specific yield. Future work may consider high-resolution soil moisture monitoring to obtain more reliable estimates of Sy, similar to the work of Nachabe et al. (2005), who used diurnal variations in total soil moisture above the water table to estimate ET.

Considering how differences in specific yield can affect estimated plant water use using water table fluctuations, calibrating the ALMANAC model to the field estimate of plant water use was problematic. This was apparent in the comparisons of monthly values of EP versus measured water use. In June, simulated EP was 21.7 mm greater than measured water use, but if a greater specific yield were used for June, the estimated plant water use would have been greater and ultimately much closer to the simulated value. Both methods of estimating ET from RC were independent of each other insofar as the model used independent values of soils, climate and plant physiology to obtain values of water use whereas the field estimates were based on water table fluctuations alone. We used the field estimated plant water use to guide the calibration of the model to ensure that our simulated plant water use was within a normal range of values given the soils and climate of the field site.

Field monitoring suggested that senescence of RC largely occurred in October when daytime water level declines were essentially the same as nighttime declines. Zedler and Kercher (2004) commented that seasonal growth of RC is typically prolonged into late fall when its green color is noticeable against the backdrop of native plant senescence. Our field monitoring suggested that although RC may have been green in October, the plant did not appear to be using appreciable quantities of water in this month. In the ALMANAC model simulation, we assumed that RC senesced its leaves during October (reached physiological maturity). The heat units (PHU) for the season were adjusted causing the leaf area to approach zero during this month.

Overall, the ALMANAC model was a useful tool to simulate water use by RC at this location. It showed similar values for plant transpiration as calculated from the water table fluctuation measurements throughout the growing season. Because plant transpiration simulation is process-based, the model can simulate changes in transpiration with different amounts of canopy cover (LAI), with different potential rooting depth of plant species, and with different values for extreme in water table depths. Its accuracy in simulating water use by RC provides encouragement for future work on water use by other plant species, especially native grasses displaced by or replacing RC.

Conclusions

The following main conclusions can be drawn from this study:

1. Water use rates by RC calculated from water table fluctuations were 3.3 mm d^{-1} in July and 2.3–2.8 mm d^{-1} in May, June, August, and September. Total water use by RC for the months of May to October was 428 mm.
2. Overall, simulated plant transpiration rates were similar to water use rates calculated from water table fluctuation measurements. Plant transpiration simulated by ALMANAC indicated near zero bias over the entire growing

season. Both simulated transpiration and water use calculated from water table fluctuations were greatest in June and July.

3. Overall agreement between modeled simulated water use and measured water use provides encouragement for further use of this model to evaluate water use by native species in floodplain environments and water use by RC in other locations.

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