ENERGY AND WATER BALANCE RESPONSE OF A VEGETATED WETLAND TO
HERBICIDE TREATMENT OF INVASIVE *PHRAGMITES AUSTRALIS*

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Abstract

The energy and water balance of a *Phragmites australis* dominated wetland in south central Nebraska was analyzed to assess consumptive water use and the potential for “water savings” as a result of vegetation eradication via herbicide treatment. Energy balance measurements were made at the field site for two growing seasons (treated and untreated), including observations of net radiation, heat storage, and sensible heat flux, which was measured using a large-aperture scintillometer. Latent heat flux was calculated as a residual of the energy balance, and comparisons were made between the two growing seasons and with model simulations to examine the relative impacts of vegetation removal and climate variability.

Observed ET rates dropped by roughly 32% between the two growing seasons, from a mean of 4.4 ± 0.7 mm day⁻¹ in 2009 (with live vegetation) to 3.0 ± 0.8 mm day⁻¹ in 2010 (with dead *P. australis*). These results are corroborated by the Agro-IBIS model simulations, and the reduction in ET implies a total “water savings” of 245 mm over the course of the growing season. The significant decreases in ET were accompanied by a more-than-doubling of sensible heat flux, as well as a ~60% increase in heat storage due to decreased LAI. Removal of *P. australis* was also found to cause measurable changes in the local micrometeorology at the wetland. Consistent with the observed increase in sensible heat flux during 2010, warmer, drier, windier conditions were observed in the dead, *P. australis* section of the wetland, compared to an undisturbed section of live, native vegetation. Modeling results suggest that the elimination of transpiration in 2010 was partially offset by an increase in surface evaporation, thereby reducing the subsequent water savings by roughly 60%. Thus, the impact of vegetation removal depends on the local climate, depth to groundwater, and management decisions related to regrowth of vegetation.

47 **Keywords**

48 Energy balance; Evapotranspiration; Water balance; *Phragmites australis*; Wetland; Agro-IBIS

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1. Introduction

Phragmites australis – or common reed – is a large, perennial grass that comes in a variety of forms, including a vigorous, invasive species in many parts of the world (Kettenring et al., 2011). While most prevalent in Europe, the species has also spread throughout much of North America, as well as temperate regions of South America, Australia, and New Zealand (Srivastava et al., 2014). Shifts in flow regimes in river and streams, and increased nutrient availability, have aided *P. australis* invasions in many regions of the world (Silliman and Bertness, 2004). Lower biodiversity, clogged waterways, and reduced streamflow are common disturbances associated with *P. australis* invasions (Rooth et al., 2003). *P. australis* can also transpire large quantities of water into the atmosphere (Headley et al., 2012; Lenters et al., 2011), which further reduces streamflow in surrounding rivers.

In addition to invasive vegetation and other land cover changes, stressors such as population growth and climate variability/change are leading to increased pressure on global water resources (Vorosmarty et al., 2000). Water scarcity issues have intensified in recent years as populations swell and water demand is increasing, including examples from the Mediterranean region (Iglasias et al., 2007), Africa (Falkenmark, 1990), and the American West, where frequent drought and increasing water demand have resulted in water shortages (Castle et al. 2014). The state of California has been dealing with its most severe drought on record (Seager et al. 2015; Wang et al. 2014) because of decreased rainfall and increased groundwater and surface water withdrawals, primarily for agricultural use (Famiglietti, 2014). Groundwater pumping is common in water-limited regions such as the Great Plains of the central United States, where large-scale agriculture is supported by withdrawals from the Ogallala aquifer. This

pumping has led to declines in the groundwater table, lake levels, and streamflow in parts of Texas, Oklahoma, Kansas, and southern Nebraska (Peterson et al., 2003).

The Republican River basin, which occupies portions of Colorado, Nebraska, and Kansas, has long experienced significant variations in streamflow. The region was hit particularly hard by the severe Dust Bowl droughts during the 1930's, followed by a massive flood in 1935. Because of the hardships faced by residents who relied on the watershed for their livelihoods, the Republican River Compact was formed in 1943 to apportion specific percentages of the water in the Republican River basin among the three states. The state of Nebraska has faced legal difficulties complying with the compact in recent decades due to declining streamflow in the Republican River. Previous studies have shown that the drop in streamflow cannot be solely explained by natural causes, such as trends in precipitation and temperature (Szilagyi, 1999; Wen and Chen, 2006). This leaves alternative explanations related to human activity, such as poor water conservation practices, increases in crop irrigation, construction of reservoirs, and changes in vegetation cover. For example, a strong, negative relationship exists between the number of irrigation wells and annual streamflow in the Republican River basin (Wen and Chen, 2006). After World War II, the use of center pivot irrigation increased dramatically, especially in Nebraska, and thousands of new irrigation wells were installed within the Republican River basin.

In addition to these issues, invasive *P. australis* began to occupy wetlands and streams near the Platte and Republican Rivers around 2004-2006 (Hicks, 2007). In 2007, the Nebraska state legislature passed Legislative Bill 701 deeming *P. australis* to be a "noxious weed," and the state initiated an herbicide program to kill the invasive species along the Platte and Republican Rivers. This program had three primary goals, namely to: 1) reduce the amount of water

consumed by transpiring riparian vegetation along waterways, 2) eliminate invasive species to restore the natural habitat and vegetation to the region, and 3) remove vegetation from stream channels to improve stream habitat for birds and other wildlife (State of Nebraska, 2007).

Control and removal of *P. australis* isn't unique to Nebraska, and similar efforts have been conducted elsewhere in North America (Kimball et al., 2010) and South Africa (Russell and Kraaij, 2008).

The primary objective of the present study is to quantify the effects of *P. australis* eradication on the energy and water balance of a vegetated wetland in the Republican River basin. This work builds on previous studies that examined the seasonal energy and water balance at the same site prior to herbicide application (Cutrell, 2010; Lenters et al., 2011; Mykleby, 2012). In this study, we compare results of new data collected during 2010, when no live *P. australis* existed in the wetland (due to herbicide application at the end of the previous growing season) with data from the previous year, prior to herbicide application. Specifically, we determined the impact of *P. australis* removal on latent heat flux (i.e., ET) within the wetland, along with other components of the energy and water balance. (It should be noted that we use the term "removal" throughout the text to denote the killing of vegetation by herbicide, even though the standing dead vegetation wasn't physically removed after spraying.) In addition to observational data, a dynamic ecosystem model, Agro-IBIS, was used to provide further quantification of the amount of water savings in the wetland attributed solely to the eradication of vegetation (i.e., controlling for other factors, such as climatic differences between the two field seasons). We hypothesize the removal of live *P. australis* would result in a drastic change in the local water and energy balance, with special emphasis placed on the decrease of transpiration from vegetation.

Other previous studies documenting large consumptive water use by *P. australis* (summarized in Table 1) have been conducted across a range of geographic and climatic regions. A few additional studies implementing herbicide or physical vegetation removal methods to intentionally alter ET show mixed results (Dugas et al., 1998; Saleh et al., 2009; Wang et al., 2012; Shafroth et al. 2005), but such examples aren't common in the literature.

<Table 1 here please>

Descriptions of the field site, instrumentation, and methodology are provided in subsequent sections, followed by a discussion of the materials and methods (section 3), results of the observed and modeled energy budget for the two field seasons (section 4), and a discussion and summary (sections 5 and 6).

2. Study site

The wetland field site (40°17.91' N, 99°57.90'W) covers an area of 0.036 km² and comprises two sections, one containing native vegetation (a mixture of *Typha latifolia*, or cattail, and *Juncus effuses*, or common rush), and the other dominated by invasive *P. australis* (Figure 1). The native section of the wetland (hereafter "N") remained largely unchanged between the 2009 and 2010 growing seasons, while the invasive *P. australis* section (hereafter "P") was sprayed with herbicide late in the 2009 growing season. Photos showing the differences between the live and dead *P. australis* are presented in Figure 2.

< Figure 1 here please >

< Figure 2 here please >

The field site is characterized by a dry subhumid climate according to the Thornthwaite (1948) classification scheme. On an annual mean basis, the daily maximum, minimum, and mean

air temperatures for the area average around 22.1 °C, 3.6 °C, and 12.8 °C, respectively, and the region receives an average of 615 mm of precipitation annually, based on 31 years of monthly climate data from 1980-2010 at the Beaver City COOP (Cooperative Observer Program) station (21 km southeast of the wetland). Mean annual snowfall for the region is 685 mm, or roughly 68 mm of water equivalent (assuming a 10:1 ratio). In this study, we define the growing season as the time between the last hard freeze in spring and the first hard freeze in fall. During 2009, these start and end dates occurred on April 11 and October 3, respectively. The growing season during 2010 was slightly longer, from April 3 to October 15. However, to make an objective comparison between years, we analyzed the common April 11 – October 3 timeframe for both seasons (a total of 176 days).

During the 2010 growing season, April, June, and August were unusually wet (187%, 227%, and 134% of normal, respectively), while May, July, and October were drier than average (64%, 73%, and 14% of normal, respectively), when compared to the long-term average between 1980-2010 (Mykleby, 2012). May and July of 2010 were also cold compared with recorded averages at the Beaver City COOP station (-2.4°C and -0.7°C, respectively), while August was warmer than normal (+0.7°C). Based on direct measurements from instrumentation located at the wetland field site, the overall growing season during 2010 was warmer and drier than 2009, with 1.3 °C warmer air temperatures and 20% lower total precipitation (Table 2). Similar interannual temperature differences were observed at the Beaver City COOP station. The wetland typically has significant amounts of standing water present (particularly early in the growing season), and mean water levels of 323 mm and 534 mm were observed during the 2009 and 2010 growing seasons, respectively. The ~210 mm higher water levels during 2010, despite drier summer conditions, are likely related to observed wetter antecedent conditions during the winter and

spring, possibly augmented by the absence of transpiring vegetation during the summer of 2010 (Mykleby, 2012).

<Table 2 here please>

3. Materials and methods

3.1 Instrumentation

Instrumentation at the field site during the 2010 growing season was identical to that deployed during the 2009 season (Lenters et al., 2011). Two meteorological towers / Bowen ratio stations (Campbell Scientific Inc., UT, USA) were deployed in the wetland in March 2009. One tower was located near the center of the P section of the wetland, roughly 40 meters away from the southern boundary and 20 meters from the northern boundary (Figure 1). The second tower was located in the N section of the wetland and has identical instrumentation. Both towers stood 6.3 meters tall and measured numerous meteorological parameters, including air temperature (at two heights), surface temperature, relative humidity, wind speed, and net radiation. Data from the meteorological stations were sampled every ten seconds and averaged over ten minute, hourly, and daily means. Additional details on the Bowen ratio instrumentation can be found in Lenters et al. (2011).

To obtain ground heat storage measurements, HOBO temperature sensors (U23-003 Pro v2 2x; Onset Computer Corporation, MA, USA) were installed on stakes and driven into the ground near each of the two meteorological stations. The sensors were deployed at six different depths (three in the water column and three in the soil), with data recorded at 20-minute intervals. Water temperature was measured at +150 mm above the soil/water interface, +450 mm, and directly at the water surface (using a floating sensor). Soil temperature was measured at -150 mm

below the soil/water interface, -450 mm, and -750 mm. The temperature measurements were then converted to heat content and integrated vertically through the soil/water column to determine the total heat storage and its temporal rate of change. Deep soil heat flux was also calculated based on the temperature gradient between the lowest two sensors and the measured soil thermal conductivity (Lenters et al. 2011).

The total rate of heat storage in the wetland, $\frac{\Delta S}{\Delta t}$, was calculated separately for three vertical layers: a) standing water, b) the upper 600 mm soil layer, and c) soil heat flux deeper than 600 mm. Heat storage rates within the *P. australis* canopy weren't considered in the analysis for 2010 due to the dry vegetation's very low water content and the low rates of heat storage already documented for the vegetated case during 2009 (Lenters et al. 2011).

Sensible heat flux was measured using the vertical air temperature gradient and data from a Large Aperture Scintillometer (LAS; Kipp & Zonen, Delft, Netherlands), which was deployed along a transect crossing the P section of the wetland (Figure 1). The LAS consists of a transmitter and receiver separated horizontally by 251 m and mounted on a steel tower (or tripod) at heights of approximately 4.8 and 4.2 meters above the ground, respectively (i.e., above the soil/water interface). Latent heat flux was calculated as a residual from the energy balance equation, described below and by Lenters et al. (2011).

3.2 Surface energy balance

The surface energy balance can be written as:

$$R_n - LE - H = \frac{\Delta S}{\Delta t}, \quad (1)$$

where Rn is net radiation, LE is latent heat flux, H is sensible heat flux, and $\frac{\Delta S}{\Delta t}$ is the total rate of heat storage in the canopy, water, and sediments. All variables in Eq. 1 are in units of W m^{-2} . We rearrange Eq. 1 to solve for the latent heat flux:

$$LE = \left(Rn - \frac{\Delta S}{\Delta t} \right) - H, \quad (2)$$

with H being measured by the LAS, in conjunction with additional meteorological variables, such as the near-surface atmospheric lapse rate (which is temporally dynamic).

All measurements, data processing, and quality assurance/quality control (QA/QC) procedures for the 2010 field season were performed similar to the methods described previously by Lenters et al. (2011) for the 2009 season. Although measurements of varying vegetation height were made at numerous intervals during the 2009 season and used in the calculations of sensible heat flux and canopy heat storage (Lenters et al., 2011), such frequent measurements were not deemed necessary for the standing dead biomass during the 2010 season. Instead, a constant, effective vegetation height of 1.8 m was assumed throughout the entire growing season. This value is similar to the effective height of the standing dead vegetation used for sensible heat calculations at the beginning of the 2009 growing season. Similar to Lenters et al. (2011) for the 2009 field season, we did not find any evidence of signal saturation during the 2010 season.

3.3 QA/QC procedures and uncertainty analysis

Similar to the QA/QC procedures described by Cutrell (2010), Lenters et al. (2011), and Mykleby (2012), periodic erroneous spikes of sensible heat flux during sunrise and sunset were removed using simple thresholds based on monthly percentiles. These gaps were then filled through regressions with ancillary meteorological measurements at the wetland field site, with the regression coefficients differing slightly from those reported by Cutrell (2010) and Lenters et

al. (2011). A similar gap-filling procedure was also used to bridge a data gap during the period 13–30 April 2010, when a severe wind event on April 13 caused a misalignment of the LAS receiver, which wasn't corrected until April 30.

Estimates of maximum likely uncertainty in the various energy balance terms were determined using the same procedures as Cutrell (2010), Lenters et al. (2011), and Mykleby (2012), namely by propagating maximum likely errors in the various measured quantities and adding them in quadrature to determine the total uncertainty in LE (i.e., Eq. 2). For 2010, using a mean water depth of 0.52 m, the maximum likely error in the hourly rate of heat storage within the wetland (canopy, water, and sediments) was found to be $\pm 60.4 \text{ W m}^{-2}$, only slightly larger than the estimate for 2009. As would be expected, the uncertainty in the heat storage term drops dramatically for daily and 5-day timescales (to $\pm 2.5 \text{ W m}^{-2}$ and $\pm 0.50 \text{ W m}^{-2}$, respectively). Taking into account all other sources of error as well (i.e., $\pm 10\%$ for R_n and $+1.1\%/-28.2\%$ for H), the resulting RMS uncertainties in LE during 2010 are $+73.9/-67.7 \text{ W m}^{-2}$ for hourly timescales and $+28.4/-17.3 \text{ W m}^{-2}$ for daily timescales. These error bounds are similar in magnitude to $\sim 46\%$ of the hourly RMS LE (144 W m^{-2}), $\sim 25\%$ of the daily RMS LE (92 W m^{-2}), and $\sim 31\%$ of the season-mean LE (72.9 W m^{-2}).

3.4 *Agro-IBIS model*

The model used in this study, known as Agro-IBIS, is an updated, continental-scale version of the IBIS terrestrial biosphere model (Foley et al. 1996; Kucharik et al. 2000), which has been modified to include crop growth, management, and complete N cycling, including nitrate leaching through the soil column through addition of a solute transport submodel (Kucharik, 2003; Kucharik and Brye, 2003). IBIS integrates hydrological, physiological,

biophysical, and ecological processes into a single, consistent model framework (Foley et al. 1996). The model has been used to simulate land surface energy, water, and carbon balances, as well as vegetation structure, on both global and regional scales (Foley et al., 1996; Foley et al., 1998; Kucharik et al., 2000; Lenters et al., 2000). IBIS explicitly models the competition between plant functional types and characterizes the response to global change drivers, such as changes in land use, air temperature, and CO₂ concentrations.

The updated Agro-IBIS model has also been extensively validated at regional (Sacks and Kucharik, 2011) and site-specific scales (Kucharik and Twine, 2007; Maayar and Sonnentag, 2009; Cuadra et al., 2011; Webler et al., 2012) and has been used to simulate both natural and managed ecosystems (Twine and Kucharik, 2009). Extensive water balance studies have also been undertaken using Agro-IBIS to simulate the impacts of managed ecosystems (i.e., crops or biofuels) on ET and runoff (Twine et al., 2004; Vanloocke et al., 2010; Vanloocke et al., 2012). Since the lower boundary condition of Agro-IBIS is specified as a unit gradient flux, the model doesn't include an explicit representation of groundwater dynamics (Soylu et al., 2011). To simulate wetland conditions for the present study, where the models soil layers are fully saturated, we have modified the lower boundary condition to a fixed soil moisture and forced the model's soil layers to be 100% saturated (Soylu, et al., 2011; Yeh and Eltahir, 2005). Absence of such forcing would otherwise result in unrealistic seasonal drying of the wetland and lower-than-observed ET rates.

The plant functional type (PFT) chosen to represent *P. australis* in Agro-IBIS was C₄ switchgrass (VanLoocke et al., 2013), due to morphological and growth similarities between the two plant types (both of which are tall, perennial grasses with thick leaves). Although *P. australis* is generally considered to be a C₃ species, previous studies have revealed C₄

characteristics as well (Rintamaki and Aro, 1985; Zheng et al., 2000). For example, young *P. australis* leaves have occasionally been observed to contain developed bundle sheath cells, which are normally indicative of C₄ plants (Antonielli et al., 2001). Also, during initial testing of the Agro-IBIS model, observed rates of latent heat flux were found to best match modeled ET rates of corn, a C₄ species. This PFT in the model has also matched well with observations from corn sites in the past (Kucharik and Twine, 2007; Maayar and Sonnentag, 2009). Use of C₃ vegetation parameters within Agro-IBIS, on the other hand, led to significant underestimates of ET, and so C₄ values were chosen for all model simulations.

Physiological parameters representative of *P. australis* (discussed in greater detail below) were measured in greenhouse growth experiments (Mykleby et al., 2015) and were incorporated into the Agro-IBIS model. These included maximum carboxylation velocity (V_{cmax} , $\mu\text{mol m}^{-2} \text{s}^{-1}$) at 25 °C, quantum use efficiency (ϕ), and specific leaf area (SLA, $\text{cm}^2 \text{g}^{-1}$). The mean value from both fertilized and non-fertilized experiments was used, since it was not known whether the wetland field site was influenced by fertilization from the surrounding agricultural fields. Other measured parameters included maximum LAI (5.4) and maximum plant height (4.2 m), both of which were measured in the field during the 2009 season. The initial LAI value for standing, dead vegetation was also required, and this value was measured to be 2.0.

Additional parameters such as the rate of decline in leaf area index (LAI), percentage of carbon allocated to leaves, and growing degree day requirements (GDD) for leaf emergence, LAI decline, plant browning, and plant maturity were adjusted to match field observations of LAI and minimize errors in model simulated energy balance and vegetation phenology. Local micrometeorological data from the wetland field site were used to drive the model, including hourly mean air temperature, incoming solar radiation, wind speed, relative humidity, and

precipitation. All meteorological forcing data used to run the model were taken from the P section of the wetland, since no simulations were performed for the N section of the wetland. To simulate the eradication of *P. australis* vegetation in the Agro-IBIS model, a growth factor permitting photosynthesis, transpiration, and LAI accumulation (known as “greenfrac1”) was simply set to 0 for the full simulation. Normally this parameter starts at 0 at the beginning of each simulation, begins to increase linearly at the onset of the growing season, and eventually reaches a final value of 1 (i.e., when the canopy is completely green). Setting greenfrac1 to 0, therefore, prohibits the formation of new, green vegetation, while still allowing for the presence of standing, dead vegetation from the previous growing season.

3.5 Model simulations

To clearly isolate the effects of climate and land cover change on the wetland energy balance during the two field seasons, five different Agro-IBIS model simulations were run under various climatic and vegetative conditions (summarized in Table 3). The first two simulations were run with the intent of mimicking as closely as possible the “real” vegetative conditions in the wetland during 2009 and 2010, such that the modeled sensible and latent heat fluxes could be effectively evaluated. Except for the tail end of the growing season, live *P. australis* vegetation existed for the majority of the 2009 season. As such, the first model run, referred to as “2009-real,” included two model adjustments to account for the herbicide spraying that occurred in the wetland on July 22, 2009, namely, a decrease in the number of GDD required for plant maturity, and an increase in the rate at which LAI declines once plant maturity is reached (Table 3). Thus, the 2009-real simulation most closely mimics the real conditions during the 2009 growing season and also provide a means of evaluating the sensitivity to model parameters under conditions of

live vegetation. The second simulation (“2010-dead”) was run for the 2010 growing season, and no live vegetation was allowed to grow in the model (i.e., $\text{greenfrac} = 0$). Since *P. australis* at the wetland site was, in fact, dead during the 2010 season, energy balance measurements during this time period provide a means of evaluating the model performance under conditions of dead, standing biomass. The third simulation, referred to as “2009-live,” was run using conditions identical to the 2009-real scenario, except that the effects of herbicide spraying late in the growing season were removed (i.e., by eliminating the earlier and faster prescribed decline in LAI). This simulation provides a slightly “truer” representation of the wetland energy balance during a (hypothetically) completely live 2009 growing season.

< Table 3 here please >

One of the difficulties in interpreting differences between the 2009 and 2010 energy balance observations is that the two seasons differ both in their micrometeorological conditions and their vegetated/non-vegetated states. Even in the model simulations, for example, one cannot simply compare the 2009-live and 2010-dead simulations to cleanly assess the role of vegetation. The Agro-IBIS model does, however, allow us to circumvent this difficulty by running two additional hypothetical scenarios (Table 3), one in which the wetland is comprised of only standing, dead biomass during 2009 (the “2009-dead” simulation) and another in which the wetland is fully vegetated during 2010 (the “2010-live” simulation). One caveat to this approach, is that, although the micrometeorological conditions for 2009 and 2010 are largely determined by external climatic influences, the underlying land cover undoubtedly has some impact on the local wetland micrometeorology as well (e.g., air temperature and sensible heat flux). Thus, it’s not possible to entirely isolate the relative roles of climate and vegetation on the wetland energy balance without performing fully coupled land-atmosphere simulations, or by creating an

experimental setup that provides a “control” wetland. Both approaches are beyond the scope of the present study.

In summary, the five Agro-IBIS model simulations allow us to examine: 1) model performance (by comparing the 2009-real and 2010-dead results with observations), 2) effects of vegetation removal (by comparing the “dead” and “live” simulations for each of the two years), and 3) impacts of climate variability (by comparing the 2009 and 2010 simulations, either live or dead, depending on the assumed vegetative conditions).

4. Results

4.1 Impact of *P. australis* removal on latent heat flux

The removal of *P. australis* vegetation resulted in a substantial drop in ET rates from 2009 to 2010. This is shown in Figures 3b and 3c, which illustrate the 5-day running mean latent heat flux and Bowen ratio, respectively (used to smooth out daily variability to better illustrate seasonal patterns). Statistically significant differences between 2009 and 2010 ET rates began to emerge in early May (Figure 3b), associated with both the emergence of green vegetation in 2009 (Lenters et al., 2011) and higher Bowen ratios in 2010 (Figure 3c). With the exception of late May through early June, these large differences in ET lingered throughout the remainder of the growing season. On average, the mean growing season ET declined by 32%, from 770 mm of water in 2009 (124 W m^{-2}) to 525 mm (84.7 W m^{-2}) in 2010. This decline in latent heat flux of $\sim 40 \text{ W m}^{-2}$ was nearly equivalent to the increase in sensible heat flux of 43 W m^{-2} (Section 4.2). In other words, the imposed change in land cover resulted in a re-partitioning of available energy from latent to sensible heat flux, and a corresponding two- to ten-fold increase in Bowen ratio (Figure 3c).

During the peak growing season (June-August), the amount of available energy ($R_n - \Delta S/\Delta t$) consumed by latent heat flux dropped from ~90% in 2009 (Figure 4c; Lenters et al. 2011) to 61% in 2010 (Figure 4d, Figure 6). Despite the 32% decline in ET from 2009 to 2010 due to *P. australis* removal, ET still continued to maintain modest rates of ~3.6 mm day⁻¹ in 2010. This indicated a significant contribution to latent heat flux from standing water evaporation, since ET from interception was likely to be minimal for dead, low-LAI leaves in a subhumid climate, and clearly no transpiration was present in 2010.

< Figure 3 here please >

Finally, we noted a sharp contrast between the diurnal cycle of ET in 2010 and 2009 (Figure 4). In particular, latent heat fluxes during the months of April and May showed essentially no mean diurnal variation in 2010 (Figure 4b), whereas 2009 exhibited values ranging from 200 W m⁻² at midday to 0 W m⁻² at night (Figure 4a, 4b). As another example, the months of JJA in 2009 revealed the mean diurnal cycle of the surface energy budget was dominated by a near balance between net radiation and latent heat flux, whereas 2010 had roughly equal contributions from H , LE , and $\Delta S/\Delta t$, with maximum hourly LE rates reduced by roughly a factor of two from those in 2009 (Figure 4c, 4d). Analogous conclusions were reached for the latter two months of the growing season (Figure 4e, 4f). In summary, we found the largest impacts of vegetation removal on ET rates occurred during peak midday hours and the midpoint of the growing season.

<Figure 4 here please>

4.2 Impact of *P. australis* removal on the energy balance

Aside from a few exceptions, the surface radiative fluxes did not exhibit any significant changes between the 2009 and 2010 growing seasons, despite the pronounced change in vegetation cover in the P section of the wetland. For example, mean growing season net radiation increased by only 3%, from 160 W m^{-2} in 2009 to 164 W m^{-2} in 2010 (Table 5), an indistinguishable change from the 10% measurement uncertainty of the net radiometer. Reduced cloud cover led to 6% higher incoming shortwave radiation in 2010 compared to 2009 (Table 2), as well as 8% higher net shortwave radiation. This was largely offset, however, by a 33% decrease in net longwave radiation during 2010, presumably in response to the warmer surface temperatures and stronger outgoing longwave radiation from the dead, nontranspiring *P. australis* vegetation. Somewhat surprisingly, relatively little change in shortwave albedo occurred between 2009 and 2010, despite the stark, visual contrast between the dark green vegetation (2009) and light brown stalks (2010) (Figure 2). We suspect, however, that the brighter vegetation's high albedo in 2010 was largely offset by significantly lower LAI, which allowed for greater penetration of solar radiation to the underlying water and dark soil. This latter effect was visually confirmed during periodic visits to the wetland in 2010.

Similar to 2009, the total $\frac{\Delta S}{\Delta t}$ term for 2010 was dominated by heat storage within the water column, rather than within the soil layers. A comparison of the cumulative heat storage rates within the water column for the two different growing seasons (both having initial values of 0 on April 11) revealed that the two years showed similar increases in total heat content until mid-May, when the 2010 values began to increase much more rapidly (Figure 5). This reflects both a faster increase in water temperature in 2010, as well as higher mean water levels during that year, compared to 2009. We hypothesize that this higher rate of heat gain in the water column during May 2010 (and also the higher rate of heat loss during August and September of

2010) was due to the lower LAI of the dead *P. australis* vegetation. In other words, lower LAI in 2010 led to less shading of the water column from incoming solar radiation in the spring and summer, and less insulation of the water column from turbulent and radiative heat loss later in the growing season.

< Figure 5 here please >

This substantial difference in total heat storage between the two years, which approaches a factor of two by mid-July (Figure 5), has important implications for other components of the wetland energy balance. There was less total available energy for sensible and latent heat fluxes in 2010, given the similar mean values of net radiation for the two years. For example, daily variations in heat storage comprised only 13% of the variability in net radiation during 2009, but increased to 25% in 2010. Similarly, the 2010 maximum rates of heat storage during peak midday hours were roughly double the rates found in 2009 (Figure 4). Thus, it was clear that the reduced LAI and biomass in 2010 were responsible for the greater partitioning of energy into heat storage within the water and soil columns, resulting in less available energy for sensible and latent heat fluxes. At the same time, greater storage of heat within the water column likely led to increased evaporation rates from areas of standing water during 2010 (relative to 2009), perhaps compensating somewhat for the drastic reductions in transpiration. Explicit measurements of the partitioning of ET into transpiration and open water evaporation rates were not available to confirm this hypothesis, but model results (discussed below in section 4.4) support this conclusion.

Sensible heat fluxes increased dramatically between the 2009 and 2010 growing seasons (Figure 3a, Figure 6). As previously noted by Lenters et al. (2011), relatively high sensible heat fluxes of 100–150 W m⁻² were common early in the 2009 growing season (i.e., when the

majority of the standing vegetation was still brown) (Figure 4a). However, these values dropped to much lower levels by mid to late May of 2009 (around 20 W m^{-2}), when green vegetation began to appear, and remained low for the remainder of the season. In contrast, 2010 showed persistently high sensible fluxes of $50\text{--}100 \text{ W m}^{-2}$ throughout the growing season (Figure 3, Figure 6), which reflects the prevalence of dead *P. australis* throughout the summer period. Averaged across each of the two growing seasons, the sensible heat flux increased by a factor of 2.3 – from 33 W m^{-2} in 2009 to 76 W m^{-2} in 2010. We attribute most of the increase in sensible heat flux to the removal of the *P. australis* vegetation and attendant changes in the local micrometeorology (i.e., warmer, drier, and windier conditions). Diurnal variations in sensible heat flux during 2010 showed patterns similar to 2009 (Figure 4), varying in accordance with the hourly net radiation. Maximum daily values, however, averaged around $150\text{--}200 \text{ W m}^{-2}$ throughout the entire 2010 growing season, in contrast to 2009 when values dropped to $\sim 50 \text{ W m}^{-2}$ by JJA (Figure 4c). As such, and similar to the results found for latent heat flux, the impacts of the vegetation eradication on sensible heat flux were found to be most prominent during midday hours (i.e., peak sunshine) and during the peak growing season.

< Figure 6 here please >

4.3 Climatic variability and vegetation impacts on micrometeorology

Average climatic conditions at the wetland during 2009 and 2010 are shown in Table 2 for the 176-day growing season (April 11 – October 3), using data from the undisturbed portion of the wetland (i.e., the N section; precipitation data were averaged across both sites to reduce uncertainty). On average, 2010 was $1.3 \text{ }^{\circ}\text{C}$ warmer than 2009, with a higher dewpoint ($+0.4 \text{ }^{\circ}\text{C}$), and lower relative humidity (-3.4%), compared to 2009). Total growing-season precipitation was

20% lower in 2010 compared to 2009, and reduced cloud cover in 2010 resulted in 6% greater incoming solar radiation than in 2009. Although average wind speeds are low at the wetland, 2010 was considerably windier, with 37% higher mean wind speeds.

As noted in section 3.1, the wetland field site contains two Bowen ratio stations, one located in the invasive, P section of the wetland, and the other positioned in the N section, which was dominated by *Typha latifolia* (cattail). The stations were located a few hundred meters apart and can be expected to measure similar climatic conditions. However, given their positioning within distinctly different vegetation stands (one of which was dead during the 2010 season), clear differences in certain meteorological variables began to emerge during the 2010 season (Table 4). These differences were much weaker (or non-existent) in 2009. For example, during the peak of the 2009 growing season (June-August; JJA), when both vegetation stands were readily transpiring, the difference in surface temperature between the two sites was only -0.3 °C (measured by a downward-facing infrared radiometer), with the P section being cooler than the N section (Table 4). However, during the 2010 season, when the P section was comprised of only dead vegetation (and a few, small sections of open water), the surface temperature measured in the P section was considerably warmer than the N section (+~2.0 °C). This represents a relatively large change in the surface temperature differential (+2.3 °C) between the two sections of the wetland from 2009 to 2010. This increased temperature differential was also reflected in air temperature (though more muted; Table 4) and had a measurable impact on relative humidity during 2010 (Table 4), which was 4.1% lower in the P section than in the N section (i.e., 71.6% relative humidity compared to 75.7%). This was in contrast to 2009, when the relative humidity was slightly higher in the P section compared to the N section of the wetland (77.7% compared to 76.4%, respectively).

< Table 4 here please >

We postulate that reduced transpiration in the P section of the wetland during 2010 was responsible for the warmer surface temperatures and air temperatures and lower relative humidity during the growing season, relative to the N section. Overall, these changes corroborate the previously noted greater partitioning of available energy into sensible heat flux and higher Bowen ratio, and also suggest enhanced atmospheric instability near the surface. Evidence for the latter was readily apparent in the local wind speed data, with 2010 showing 82% higher average JJA wind speeds in the P section compared to the N section. In 2009, on the other hand, this difference was almost a factor of two less, showing 45% higher wind speeds in the P section compared to the N section. This indicates that, although the P section of the wetland was generally windier than the N section (due to the lower level of tree sheltering from nearby vegetation), this difference in wind speed was especially pronounced in 2010, when the *P. australis* vegetation was in the form of standing dead biomass. Altogether, these warmer, drier, windier conditions in the P section during 2010 are consistent with the significant increase in sensible heat flux and decrease in ET observed in response to the herbicide application the preceding year.

4.4 Comparison with model results

As discussed in section 3.5, the primary objective of the Agro-IBIS model simulations was to isolate the effects of vegetation removal from that of climatic variability between the two measurement years. For model validation purposes, we first compared the results of the 2009-real and 2010-dead model simulations with observations of *LE* and *H* from these same two years (Figure 7). The model simulated latent heat flux compared well with observations for both 2009

and 2010 (Figure 7a), capturing the majority of the seasonal and short-term variability and with almost no bias in the seasonal mean LE . The model simulated sensible heat flux also captured much of the same variability seen in the observed H (Figure 7b), but showed an underestimation of early season H in both 2009 and 2010, as well as an underestimation of late-season H in 2010 (Figure 7b). A summary of the observed and modeled energy balance for the two growing seasons is shown in Table 5. The model exhibited very little bias in the simulated LE ($\sim 3\%$), but moderate underestimation of H in both years ($\sim 21\%$). It is worth noting, however, that the model's average underestimate of H (11.4 W m^{-2}) was comparable in magnitude to a similar underestimate in net radiation (12.3 W m^{-2}). Furthermore, this 7-8% difference between modeled and observed Rn was within the observational uncertainties, indicating that the modeled H was also likely within the error bounds of the observed sensible heat flux.

< Figure 7 here please >

< Table 5 here please >

A summary of the simulated effect of vegetation removal on the wetland energy balance is provided in Table 6, which shows “live” and “dead” conditions for both years, as well as the modeled difference (dead minus live) and, for comparison, the measured difference from the observations (2010 minus 2009). Both simulation years showed similar effects of vegetation removal in all energy balance components, indicating that the effects of climatic variability between years were relatively insignificant compared to the effects of vegetation removal. Large decreases in LE (31-32%) and increases in H (128-142%) were found in the model simulations when the *P. australis* was killed, and these changes were comparable in magnitude to the observed differences (Table 6). Relatively minimal changes, however, were found between the “live” and “dead” simulations of net radiation (and heat storage rate), and this was consistent

with the observations. It is also interesting to note that net radiation was the only simulated energy balance parameter that showed larger year to year differences than the changes induced by vegetation removal (Table 6). These differences, however, were relatively small ($\sim 9 \text{ W m}^{-2}$) and, together with other meteorological differences between 2009 and 2010 (Table 2), did not translate into large year-to-year changes in the modeled H and LE (Table 6).

< Table 6 here please >

Additional insight into the hydrologic impacts of the imposed vegetation change can be gained by examining the simulated partitioning of ET into transpiration (T) and evaporation (E), as well as time series of modeled E , T , and ET for the live simulations, and E for the dead scenario (also equal to ET, since $T = 0$) (Figure 8). Each of the simulation results is shown as an average over the two-year period 2009-2010 in order to focus on vegetation effects, rather than the small effects of year-to-year climatic differences. Except for the very beginning and end of the growing season, transpiration in the “live” scenario clearly dominated the total ET, showing a peak in mid-June (Figure 8). This was in contrast to E , which tended to be highest early and late in the season, with lower E in mid-season due to vegetation influences (e.g., wind sheltering and shading of incoming radiation). Once the vegetation was killed in the “dead” simulations, total ET decreased greatly due to the absence of green, transpiring vegetation in the wetland (Figure 8). Standing water evaporation, however, increased by nearly a factor of three, from a growing season total of 190 mm in the “live” simulations to 530 mm in the “dead” simulations. This 340 mm increase, however, was not enough to compensate for the significant, 580 mm decline in transpiration, leading to a 32% drop in total ET and an overall “water savings” of 240-250 mm as a result of vegetation removal (Table 7). This amount of water was nearly identical to the observed decline in ET from 2009 to 2010 (Table 7) and was also similar to the ~ 210 -mm higher

water levels observed in the wetland during the 2010 growing season (despite 20% lower total precipitation than 2009).

< Table 7 here please >

< Figure 8 here please >

5. Discussion

The wetland field site in the current study is located at ~41°N, in a dry subhumid climate. Our results show an average daily ET of $3.0 \pm 0.8 \text{ mm day}^{-1}$ in the presence of dead *P. australis*, which is 32% lower than the 770 mm of ET observed when there was live *P. australis* in the wetland, and average ET rates were around $4.4 \pm 0.7 \text{ mm day}^{-1}$ (Lenters et al., 2011). The reduction in latent heat flux in 2010 coincided with higher sensible heat flux and an increased rate of heat storage in the wetland water column. A review of previous *P. australis* studies from the literature shows that a majority took place in similar, midlatitude climatic regimes (Table 1). Most of these studies also include varying seasonal time scales, so using both average and maximum daily rates of ET provides the best means for comparison. Because of varying time scales, reported rates of potential and reference ET should not be over-interpreted, as different methods of estimation, as well as differing climate regimes can lead to increased variability between field sites.

A comparison of *P. australis* ET rates across climatic regimes (e.g., latitude, mean temperature) shows some degree of correspondence (Table 1). In southern Europe, for example, where the Mediterranean climate produces warm, dry summers, high rates of season-mean ET (~8 to 32.5 mm day^{-1} , depending on study site and methods) were reported in northern and southern Italy (Milani and Toscano, 2013; and Borin et al., 2011) and southeast Spain (Moro et

al., 2004; Sanchez-Carrillo et al., 2004). Field sites in more continental climatic regions, on average, exhibited lower mean daily ET than Mediterranean climates, ranging from 3.75 – 4.1 mm day⁻¹ (for vegetation and open water, respectively; Burba et al., 1999a and b), 4.4 mm day⁻¹ (Lenters et al., 2011), and 5.5 mm day⁻¹ (Irmak et al., 2013) for *P. australis* stands in Nebraska. Furthermore, ET rates from more northern latitudes (Smid, 1975; Peacock and Hess, 2004; Anda et al. 2015) showed similar results to those found in Nebraska, although Zhou and Zhou (2009) found slightly lower mean daily ET rates during the growing season (2.1 mm day⁻¹) in northeast China at a similar latitude (Table 1). The lower rates observed in China compared to results in this study and other sites in Nebraska could be attributed to measurement methods, vegetation characteristics, and/or differences in climate, such as the average annual temperature, which is 3.3 °C cooler than the field site in the present study (Mohamed et al. 2012).

Finally, while the current study could not directly investigate open water evaporation rates, due to the standing dead vegetation at the field site, comparisons were made between published open water evaporation rates and *P. australis* ET rates in adjacent field sites (Table 1), in order to examine which environment consumed more water, similar to the methodology of the current study. Results from the present study indicate removal of *P. australis* vegetation reduces water consumption via transpiration, despite an increase in standing-water evaporation beneath the dead vegetation. Although previous studies have concluded open-water evaporation rates are greater than ET rates of *P. australis* (Burba et al. 1999b; Sanchez-Carrillo et al. 2004), such a result clearly depends on the degree of shading and wind sheltering provided by any adjacent standing vegetation. Herbst and Kappen (1999), for example, reported ET rates of *P. australis* can be almost double the evaporation rates found in open water.

6. Summary

P. australis can be an aggressive invasive species that chokes waterways with thick, dense vegetation and transpires water at very high rates, impacting ecosystems and the services they provide. Flood suppression (e.g., as a result of damming), as well as reduction of wildfires have removed natural disturbances that might otherwise inhibit the proliferation of this invasive species. Eradication efforts are ongoing in parts of the United States, where ecosystem services including wildlife, biodiversity, aesthetics, and water supplies are threatened. Results from the present study show that the removal of invasive *P. australis* from wetlands and riparian zones in semi arid regions can have a significant impact on the local energy and water balance, at least during the first year after vegetation eradication.

We examined the effects of invasive *P. australis* removal on the observed and modeled energy and water balance of a wetland in south central Nebraska, with the primary goal to determine the potential water savings that could be achieved through vegetation removal. This was done to simulate, on a small, site-specific scale, the effects of broader actions already taken in the state of Nebraska, where invasive species have been removed from riparian zones since 2007. Results of this study are likely to be transferrable to other semi-arid regions where invasive plants can consume a significant amount of near-surface water in wetlands and riparian zones (e.g., Dugas et al., 1998; Sanchez-Carillo et al., 2001).

Meteorological Bowen ratio stations and an LAS were used to directly measure sensible heat fluxes at the wetland field site, while latent heat flux was calculated as a residual of the surface energy balance. Model simulations were also implemented to further compare with the observations and isolate the relative roles of vegetation removal and climate variability. Total accumulated ET during the 2010 growing season, when the *P. australis* was comprised of dead

standing biomass, was 525 mm (3.0 ± 0.8 mm day⁻¹, on average). This was 32% lower than the 770 mm of ET observed during the 2009 growing season, when the *P. australis* was still alive (average ET rate of 4.4 ± 0.7 mm day⁻¹). These results are corroborated by the Agro-IBIS model simulations, which show good agreement with the observed energy balance and similar changes in ET. We conclude, therefore, that 240-250 mm of “water savings” were achieved during the 2010 growing season as a result of the removal (i.e., spraying) of *P. australis* vegetation.

The present study was limited to only a two-year period, so we cannot directly address questions related to long-term response. We do note, however, that our wetland study site was perennially inundated with significant amounts of standing water. As a result, we found a significant *increase* in modeled open water evaporation in the simulations with dead *P. australis* (530 mm, as compared to 190 mm in the presence of live vegetation), despite the sheltering effects of the standing dead vegetation. This 340 mm increase in open water evaporation partially compensated for the 580 mm decrease in transpiration that resulted from the vegetation removal, thereby lowering the potential water savings by roughly 60%. We conclude, therefore, that other semi-arid regions with shallow, but *subsurface*, groundwater would likely realize even greater water savings than were found in the present study, so long as the vegetation that grows back does not transpire at rates in excess of the local open water evaporation rate. Finally, we also note that, despite having reduced biomass, the presence of standing, dead *P. australis* helps minimize below-canopy evaporation, compared to what might otherwise occur from open water, bare soil, or grass (through wind sheltering and radiative effects). Whether or not this dead standing vegetation is physically removed, therefore, is an additional consideration that must be taken into account when developing effective water savings strategies for wetlands and riparian zones.

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References

- Anda, A., Soos, G., Silva, J. A., & Kozma-Bognar, V., 2015. Regional evapotranspiration from a wetland in Central Europe, in a 16-year period without human intervention. *Agricultural and Forest Meteorology*, 205, 60-72.
- Antonielli, M., Pasqualini, S., Batini, P., Ederli, L., Massacci, A., Loreto, F., 2002. Physiological and anatomical characterisation of *Phragmites australis* leaves. *Aquatic Botany* 72, 55-66.
- Borin, M., Milani, M., Salvato, M., & Toscano, A., 2011. Evaluation of *Phragmites australis* (Cav.) Trin. evapotranspiration in Northern and Southern Italy. *Ecological Engineering*, 37(5), 721-728.
- Burba, G.G., Verma, S.B., & Kim, J. 1999. Surface energy fluxes of *Phragmites australis* in a prairie wetland. *Agricultural and Forest Meteorology*, 94(1), 31-51.
- Burba, G.G., S.B. Verma, and J. Kim., 1999. A Comparative Study of Surface Energy Fluxes of Three Communities (*Phragmites Australis*, *Scirpus Acutus*, and Open Water) in a Prairie Wetland Ecosystem. *Wetlands* 19(2), 451-57.
- Castle, S. L., Thomas B.F., Reager J.T., Rodell M., Swenson S.C., and Famiglietti J.S., 2014. Groundwater Depletion during Drought Threatens Future Water Security of the Colorado River Basin. *Geophysical Research Letters* 41(16), 5904-911.
- Clulow, A. D., Everson, C. S., Mengistu, M. G., Jarmain, C., Jewitt, G. P., Price, J. S., & Grundling, P., 2012. Measurement and modelling of evaporation from a coastal wetland in Maputaland, South Africa. *Hydrology and Earth System Sciences*, 16(9), 3233-3247.
- Cuadra, S. V., M. H. Costa, C. J. Kucharik, H. R. Da Rocha, J. D. Tatsch, G. Inman-Bamber, R. P. Da Rocha, C. C. Leite, and O. M. R. Cabral., 2011. A Biophysical Model of Sugarcane Growth. *Global Change Biology Bioenergy* 4(1), 36-48.

702 Cutrell, G.T., 2010. Seasonal Energy and Water Balance of a *Phragmites australis*-Dominated
 703 Wetland in the Republican River Basin (Southwestern Nebraska, USA). Master's Thesis.
 704 University of Nebraska, Lincoln. 114 pp.

705 Dugas, W.A., Hicks, R.A., Wright, P., 1998. Effect of removal of *Juniperus ashei* on
 706 evapotranspiration and runoff in the Seco Creek watershed. Water Resources
 707 Research 34(6), 1499-1506.

708 Falkenmark, M., 1990. Rapid Population Growth and Water Scarcity: The Predicament of
 709 Tomorrow's Africa. Population and Development Review 16, 81-94.

710 Famiglietti, J. S., 2014. The global groundwater crisis. Nature Climate Change, 4(11), 945-948.

711 Foley, J. A., Prentice, C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S., and Haxeltine, A.
 712 1996. An integrated biosphere model of land surface processes, terrestrial carbon balance,
 713 and vegetation dynamics. Global Biogeochemical Cycles 10(4) 603-628.

714 Headley, T., Davison, L., Huett, D., & Müller, R., 2012. Evapotranspiration from subsurface
 715 horizontal flow wetlands planted with *Phragmites australis* in sub-tropical Australia.
 716 Water Research, 46(2), 345-354.

717 Herbst, M., & Kappen, L., 1999. The ratio of transpiration versus evaporation in a reed belt as
 718 influenced by weather conditions. Aquatic Botany, 63(2), 113-125.

719 Hicks, Nancy. Invasive Vegetation Takes Hold in Platte River. JournalStar.com. Lincoln
 720 Journal-Star, 12 May 2007.

721 Iglesias A., Garrote L., Flores F., and Moneo M., 2007. Challenges to Manage the Risk of Water
 722 Scarcity and Climate Change in the Mediterranean. Water Resources Management 21(5),
 723 775-88.

724 Irmak, S., Kabenge, I., Rudnick, D., Knezevic, S., Woodward, D., & Moravek, M., 2013.
 725 Evapotranspiration crop coefficients for mixed riparian plant community and
 726 transpiration crop coefficients for Common reed, Cottonwood and Peach-leaf willow in
 727 the Platte River Basin, Nebraska-USA. *Journal of Hydrology*, 481, 177-190.

728 Kettenring, K. M., McCormick, M. K., Baron, H. M., & Whigham, D. F., 2011. Mechanisms of
 729 *Phragmites australis* invasion: Feedbacks among genetic diversity, nutrients, and sexual
 730 reproduction. *Journal of Applied Ecology*, 48(5), 1305-1313.

731 Kimball, M. E., Able, K. W., & Grothues, T. M., 2010. Evaluation of Long-Term Response of
 732 Intertidal Creek Nekton to *Phragmites australis* (Common Reed) Removal in Oligohaline
 733 Delaware Bay Salt Marshes. *Restoration Ecology*, 18(5), 772-779.

734 Kucharik, C.J., J.A. Foley, C. Delire, V.A. Fisher, M.T. Coe, S.T. Gower, J. Lenters, C. Molling,
 735 J.M. Norman and N. Ramankutty, 2000. Testing the performance of a dynamic global
 736 ecosystem model: Water balance, carbon balance, and vegetation structure. *Global*
 737 *Biogeochemical Cycles* 14(3), 795-825.

738 Kucharik, C.J., 2003. Evaluation of a process-based Agro-Ecosystem Model (Agro-IBIS) across
 739 the US corn belt: simulations of the interannual variability in maize yield. *Earth*
 740 *Interactions* 7, 1–33.

741 Kucharik, C.J. and K.R. Brye, 2003. Integrated BIOSphere Simulator (IBIS) yield and nitrate loss
 742 predictions for Wisconsin maize receiving varied amounts of nitrogen fertilizer. *Journal*
 743 *of Environmental Quality* 32, 247-268.

744 Kucharik C.J., Twine T.E., 2007. Residue, respiration, and residuals: evaluation of a dynamic
 745 agroecosystem model using eddy flux measurements and biometric data. *Agricultural*
 746 *and Forest Meteorology* 146, 134–158.

747 Lenters, J. D., M. T. Coe, and J. A. Foley, 2000. Surface water balance of the continental United
 748 States, 1963–1995: Regional evaluation of a terrestrial biosphere model and the
 749 NCEP/NCAR reanalysis. *Journal of Geophysical Research* 105(D17), 22,393– 22,425.

750 Lenters, J.D., Cutrell, G.T., Istanbuluoglu, E., Scott, D.T., Herrman, K.S., Irmak, A., Eisenhauer,
 751 D.E., 2011. Seasonal energy and water balance of a *Phragmites australis*-dominated
 752 wetland in the Republican River basin of south-central Nebraska (USA). *Journal of*
 753 *Hydrology* 408, 19-34.

754 Maayar, M. El, and O. Sonnentag., 2009. Crop Model Validation and Sensitivity to Climate
 755 Change Scenarios. *Climate Research* 39, 47-59.

756 Marks, M., Lapin, B., Randall, J., 1994. *Phragmites australis* (*P. communis*): Threats,
 757 management, and monitoring. *Natural Areas Journal* 14, 285–294.

758 Milani, M., & Toscano, A., 2013. Evapotranspiration from pilot-scale constructed wetlands
 759 planted with *Phragmites australis* in a Mediterranean environment. *Journal of*
 760 *Environmental Science and Health, Part A*, 48(5), 568-580.

761 Mohamed, Y., Bastiaanssen, W., Savenije, H., Hurk, B. V., & Finlayson, C., 2012. Wetland
 762 versus open water evaporation: An analysis and literature review. *Physics and Chemistry*
 763 *of the Earth, Parts A/B/C*, 47-48, 114-121.

764 Moro, M. J., Domingo, F., & López, G., 2004. Seasonal transpiration pattern of *Phragmites*
 765 *australis* in a wetland of semi-arid Spain. *Hydrological Processes*, 18(2), 213-227.

766 Mykleby, P.M., 2012. Water and Energy Balance Response of a Riparian Wetland to the
 767 Removal of *Phragmites Australis*. Master's Thesis. University of Nebraska, Lincoln. 116
 768 pp.

769 Mykleby, P.M., Awada, T., Lenters, J.D., Bihmidine, S., Yarina, A.J., Young, S.L., 2015.
770 Effects of Nitrogen Fertilization and Temperature on Gas Exchange in Native and
771 Introduced Common Reed (*Phragmites australis*). Great Plains Research 25(1), 63-74.

772 Peacock, C. E., & Hess, T. M., 2004. Estimating evapotranspiration from a reed bed using the
773 Bowen ratio energy balance method. Hydrological Processes, 18(2), 247-260.

774 Peterson, J.M., Marsh, T.L., Williams, J.R., 2003. Conserving the Ogallala Aquifer: Efficiency,
775 Equity, and Moral Motives. Choices, AAEA, 15-18.

776 Rintamaki, E., Aro, E.M., 1985. Photosynthetic and photorespiratory enzymes in widely
777 divergent plant species with special reference to the moss *Ceratodon purpureus*:
778 properties of ribulose biphosphate carboxylase/oxygenase, phosphoenolpyruvate
779 carboxylase and glycolate oxidase. Journal of Experimental Botany 36, 1677-1684.

780 Rooth, J. E., Stevenson, J. C., & Cornwell, J. C., 2003. Increased sediment accretion rates
781 following invasion by *Phragmites australis*: The role of litter. Estuaries, 26(2), 475-483.

782 Russell, I. A., & Kraaij, T., 2008. Effects of cutting *Phragmites australis* along an inundation
783 gradient, with implications for managing reed encroachment in a South African estuarine
784 lake system. Wetlands Ecology and Management Wetlands Ecol Manage, 16(5), 383-393.

785 Sacks, W. J., and C. J. Kucharik., 2011. Crop Management and Phenology Trends in the U.S.
786 Corn Belt: Impacts on Yields, Evapotranspiration and Energy Balance. Agricultural and
787 Forest Meteorology 151.7, 882-94.

788 Saleh, A., Wu H., Brown C.S., Teagarden F.M., Mcwilliams S.M., Hauck L.M., and Millican
789 J.S., 2009. Effect of Brush Control on Evapotranspiration in the North Concho River
790 Watershed Using the Eddy Covariance Technique. Journal of Soil and Water
791 Conservation 64(5), 336-49.

792 Sanchez-Carrillo S, Alvarez-Cobelas M, Angeler DG, Benitez M., 2001. A simple method for
 793 estimating water loss by transpiration in wetlands. *Hydrologic Sciences Journal* 46, 537–
 794 52.
 795 Seager R., Hoerling M., Schubert S., Wang H., Lyon B., Kumar A., Nakamura J., and Henderson
 796 N., 2015. Causes of the 2011–14 California Drought*. *Journal of Climate* 28(18) 6997-
 797 7024.
 798 Shafroth, P. B., Cleverly, J. R., Dudley, T. L., Taylor, J. P., Riper, C. V., Weeks, E. P., & Stuart,
 799 J. N., 2005. Control of Tamarix in the Western United States: Implications for Water
 800 Salvage, Wildlife Use, and Riparian Restoration. *Environmental Management*, 35(3),
 801 231-246.
 802 Silliman, B. R., & Bertness, M. D., 2004. Shoreline Development Drives Invasion of *Phragmites*
 803 *australis* and the Loss of Plant Diversity on New England Salt Marshes. *Conservation*
 804 *Biology*, 18(5), 1424-1434.
 805 Smid, P., 1975. Evaporation From a Reedswamp. *Journal of Ecology* 63(1), 299-309.
 806 Soylu, M.E., Istanbuluoglu, E., Lenters, J.D., and Wang, T., 2011. Quantifying the Impact of
 807 groundwater depth on evapotranspiration in a semi-arid grassland region. *Hydrology and*
 808 *Earth System Sciences* 15, 787-806.
 809 Srivastava, J., Kalra, S. J., & Naraian, R., 2014. Environmental perspectives of *Phragmites*
 810 *australis* (Cav.) Trin. Ex. Steudel. *Applied Water Science*, 4(3), 193-202.
 811 State of Nebraska, 2007. LB 701, 100th Legislature, 1st Sess. (2007).
 812 Szilagyi, J., 1999. Streamflow depletion investigations in the Republican River basin:
 813 Colorado, Nebraska, and Kansas. *Journal of Environmental Systems* 27 (3), 251–
 814 263.

815 Twine, T. E., C. J. Kucharik, and J. A. Foley., 2004. Effects of Land Cover Change on the
816 Energy and Water Balance of the Mississippi River Basin. *Journal of Hydrometeorology*
817 5(4), 640-55.

818 Twine, T.E., Kucharik, C.J, and Foley, J.A., 2005. Effects of El Niño–Southern Oscillation on
819 the Climate, Water Balance, and Streamflow of the Mississippi River Basin. *Journal of*
820 *Climate*, 18, 4840-4861.

821 Twine, T. E., and C. J. Kucharik., 2009. Climate Impacts on Net Primary Productivity Trends in
822 Natural and Managed Ecosystems of the Central and Eastern United States. *Agricultural*
823 *and Forest Meteorology* 149(12), 2143-161.

824 Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. *Geographical*
825 *Review* 38 (1), 55–94.

826 VanLoocke, A., Bernacchi, C.J., Twine, T.E., 2010. The impacts of *Miscanthus giganteus*
827 production on the Midwest US hydrologic cycle. *Global Change Biology Bioenergy* 2,
828 180-191.

829 Vanloocke, A., T. E. Twine, M. Zeri, and C. J. Bernacchi. A Regional Comparison of Water Use
830 Efficiency for *Miscanthus*, Switchgrass and Maize. *Agricultural and Forest Meteorology*
831 164, 82-95.

832 Vorosmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global Water Resources:
833 Vulnerability from Climate Change and Population Growth. *Science*, 289, 284-288.

834 Wang, Q., Yang Z., Liu Q., and Zhao Y.. 2012. Water Preservation and the Ecological Effects of
835 Removing Leaves from Stalks for a Reed Dominant Wetland. *Ecological Engineering* 49,
836 118-22.

837 Wang, S.Y., Hipps L., Gillies R.R., and Yoon J.H., 2014. Probable causes of the abnormal ridge

838 accompanying the 2013–2014 California drought: ENSO precursor and anthropogenic
839 warming footprint, *Geophys. Res. Lett.*, 41, 3220–3226.

840 Webler, G., D.R. Roberti, Santiago V. Cuadra, V.S. Moreira, and M.H. Costa., 2012. Evaluation
841 of a Dynamic Agroecosystem Model (Agro-IBIS) for Soybean in Southern Brazil. *Earth*
842 *Interactions* 16(12), 1-15.

843 Wen, F., Chen, X., 2006. Evaluation of the impact of groundwater irrigation on
844 streamflow in Nebraska. *Journal of Hydrology* 327, 603–617.

845 Winter, J.M., Pal, J.S., Eltahir, E.A., 2009. Coupling of Integrated Biosphere Simulator to
846 Regional Climate Model Version 3. *Journal of Climate*, 22, 2743-2756.

847 Yeh, P. J. F., and E. A. B. Eltahir. Representation of Water Table Dynamics in a Land Surface
848 Scheme. Part I: Model Development. *Journal of Climate* 18(12), 1861-880.

849 Zheng, W.J., Zheng, X.P., and Zhang, C.L., 2000. A survey of photosynthetic carbon metabolism
850 in 4 ecotypes of *Phragmites australis* in northwest China: Leaf anatomy, ultrastructure,
851 and activities of ribulose 1,5-bisphosphate carboxylase, phosphoenolpyruvate
852 carboxylase and glycollate oxidase. *Physiologica Plantarum*, 110, 201-208.

853 Zhou, L., & Zhou, G., 2009. Measurement and modelling of evapotranspiration over a reed
854 (*Phragmites australis*) marsh in Northeast China. *Journal of Hydrology*, 372(1-4), 41-47.

<i>Citation</i>	<i>Location</i>	<i>Study Duration</i>	<i>Size of Study Area</i>	<i>Vegetation</i>	<i>Method</i>	<i>Atmospheric Evaporative Demand (AED)</i>	<i>Key Results</i>
Smid (1975)	Czechoslovakia (48°46' N)	May-Oct 1973	N/A	<i>P. communis</i>	BREB	N/R	Daily max ET: 6.9 mm day ⁻¹
Burba et al. (1999a)	Nebraska (42°30'N)	June-Oct 1994	2.5 km ²	<i>P. australis</i> , <i>S. acutus</i>	BREB	N/R	Daily ET: 3.5-6.5 mm day ⁻¹ Season-mean ET: 3.75 mm day ⁻¹
Burba et al. (1999b)	Nebraska (42°30'N)	May-Oct 1994	2.5 km ²	<i>P. australis</i> , <i>S. acutus</i>	BREB	N/R	<i>S. acutus</i> ET: 3.5 mm day ⁻¹ <i>P. australis</i> ET: 3.8 mm day ⁻¹ Open-water E: 4.1 mm day ⁻¹
Moro et al. (2004)	Spain (38°10' N)	May-Oct 2000	2.00 km ²	<i>P. australis</i>	Sap flow	<i>ETp</i> : 1600 mm yr ⁻¹ (Hargreaves)	Daily max ET: 23 mm day ⁻¹ Season-mean ET: 11.0 mm day ⁻¹
Peacock and Hess (2004)	England (51°19'N)	June-Aug 2001	2.43 km ²	<i>P. australis</i>	BREB	N/R	Daily ET: 0.5 – 5.0 mm day ⁻¹
Sanchez-Carrillo et al. (2004)	Central Spain (39°08'N)	1993-1998	16.75 km ²	<i>P. australis</i> , <i>C. mariscus</i> , <i>T. domingensis</i>	BREB	<i>ETp</i> : 850 mm yr ⁻¹ (Thornthwaite)	Open-water E: 8.0 mm day ⁻¹ <i>P. australis</i> ET: 7.7 mm day ⁻¹ <i>C. mariscus</i> ET: 15.6 mm day ⁻¹ <i>T. domingensis</i> ET: 4.9 mm day ⁻¹
Zhou and Zhou (2009)	NE China (41°08')	2005-2006	900 km ²	<i>P. australis</i>	Eddy-Covariance	<i>ETr</i> : 815 mm yr ⁻¹ (FAO 56)	Season-mean ET: 2.1 mm day ⁻¹ , Daily max ET: 5.8 mm day ⁻¹
Borin et al. (2011)	Italy (45°49'N) (37°20'N)	2008-2009	0.2 m ²	<i>P. australis</i>	Water displacement	Season-mean / daily max <i>ETr</i> : 3.6 / 5.1 and 5.2 / 7.8 mm day ⁻¹ (N. and S. Italy, respectively) (Penman-Monteith)	Season-mean ET: 25.4 mm day ⁻¹ (N. Italy), and 32.5 mm day ⁻¹ (S. Italy)
Lenters et al. (2011)	Nebraska, USA (40°17'N)	Apr-Oct 2009	0.036 km ²	<i>P. australis</i>	Energy balance/LAS	<i>ETp</i> : 861 mm yr ⁻¹ (Priestly-Taylor)	Daily max ET: 8.2 mm day ⁻¹ Season-mean ET: 4.4 mm day ⁻¹
Irmak et al. (2013)	Nebraska, USA (41°08')	May-Oct 2009-2010	0.064 km ²	<i>P. australis</i> , <i>P. aigeiros</i> , <i>S. amygdaloides</i>	BREB	Season-mean <i>ETr</i> : 4.2 mm day ⁻¹ ; Daily Max <i>ETr</i> : 11.0 mm day ⁻¹ (Penman-Monteith)	Season-mean ET: 3.8, 5.5 mm day ⁻¹ ; Daily max ET: 8.5, 10.6 mm day ⁻¹
Milani and Toscano (2013)	Siciliy, Italy (37°30'N)	Jun-Nov 2009, Apr-Nov 2010	4.5 m ²	<i>P. australis</i>	Water displacement	<i>ETr</i> : 3.7 mm day ⁻¹ (Penman-Monteith)	Season-mean ET: 24.7, 16.7 mm day ⁻¹ for 2 growing seasons; Daily max ET: 7.8, 6.1 mm day ⁻¹
Anda et al. (2015)	Hungary (46°39'N)	2003-2012	52 km ²	<i>P. australis</i> , <i>C. riparia</i>	Penman-Monteith	<i>ETr</i> : 3.4 mm day ⁻¹ (Penman-Monteith)	Season-total ET: <i>P. australis</i> : 4.0 mm day ⁻¹ <i>C. riparia</i> : 3.7 mm day ⁻¹

Mykleby et al. (2016)	Nebraska, USA (40°17'N)	Apr-Oct 2010	0.036 km ²	Dead <i>P.</i> <i>australis</i>	Energy balance/LAS	<i>ETp</i> : 861 mm yr ⁻¹ (Priestly- Taylor)	Daily max ET: 6.9 mm day ⁻¹ Season-mean ET: 3.0 mm day ⁻¹
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Table 1. Summary of relevant energy and water balance field studies from different wetlands around the world. BREB refers to the Bowen ratio / energy balance method. Studies were ordered chronologically, then alphabetically.

Table 2. Average micrometeorological conditions at the wetland field site during the 2009 and 2010 growing seasons (April 11 – October 3). Data from only the undisturbed, native side of the wetland were used to calculate seasonal means, except for precipitation, which was averaged across the native and *P. australis* portions of the wetland. Asterisks denote instances where interannual differences in seasonal means exceeded instrument uncertainty.

	2009	2010
Precipitation (mm)	464*	369*
Air temperature (°C)	18.7*	20.0*
Dewpoint (°C)	13.5	13.9
Relative humidity (%)	74.9	71.5
Wind speed (m s ⁻¹)	0.49*	0.67*
Incoming shortwave radiation (W m ⁻²)	256	271

Table 3. List of the five Agro-IBIS simulations completed for this study, along with the values of various model parameters. Besides GDD (in °C-days), all other parameters are unitless. *laicons* is a constant that regulates the decline of green LAI once the GDD threshold is met. *blai* represents brown LAI, while *bsai* is brown stem area index (SAI). Asterisks indicate the two model simulations that were used to validate against observed energy balance data.

Agro-IBIS model parameters						
<i>Simulation name</i>	<i>Initial greenfrac</i>	<i>laicons</i>	<i>GDD until LAI decline</i>	<i>Starting blai</i>	<i>bsai</i>	<i>blai decline</i>
2009-real*	1	5.0	1270	1.5	6.0 x blai	0.01
2010-dead*	0	-	-	0.9	8.5 x blai	0.00
2009-live	1	1.0	1540	1.5	6.0 x blai	0.01
2009-dead	0	-	-	0.9	8.5 x blai	0.00
2010-live	1	1.0	1540	1.5	6.0 x blai	0.01

Table 4. Comparison of average meteorological conditions between the native (N) and *P. australis* (P) sections of the wetland for 2009 and 2010 during the peak, summer growing season (June 1 – August 31). Variations in wind speed are expressed as a percent difference, rather than an absolute difference. Surface temperature measurements were obtained from a downward-facing infrared radiometer. Note the warmer, drier, windier conditions in the P section during 2010 (compared to the N section), when the *P. australis* was dead. Asterisks denote instances where the seasonal mean differences exceed instrument uncertainty, while the † symbol indicates differences that are statistically significant, based on Student's t-test ($p < 0.05$).

	N (2009)	P (2009)	Difference (P minus N)	N (2010)	P (2010)	Difference (P minus N)
Surface temperature (°C)	20.8	20.5	-0.3	23.2	25.2	+2.0 * †
Air Temperature (°C)	21.3	21.4	+0.1 *	23.2	24.0	+0.8 * †
RH (%)	76.4	77.7	+1.3	75.7	71.6	-4.1
Wind speed (m s ⁻¹)	0.40	0.58	+45% *	0.55	1.00	+82% * †

Table 5. Observed and modeled season-mean (April 11 – October 3) energy balance components for live and dead *P. australis* conditions, as well as the difference (model – observations; expressed as a percent change, in parentheses).

	Live <i>P. australis</i>			Dead <i>P. australis</i>		
	2009 (observed)	2009-real (modeled)	Difference	2010 (observed)	2010-dead (modeled)	Difference
Rn (W m ⁻²)	160	147	-12.8 (-8%)	164	153	-11.8 (-7%)
LE (W m ⁻²)	124	121	-3.6 (-3%)	84.7	87.3	+2.6 (+3%)
H (W m ⁻²)	32.7	25.8	-6.9 (-21%)	75.7	59.9	-15.8 (-21%)
$\Delta S/\Delta t$ (W m ⁻²)	3.1	0.7	-2.4 (-77%)	4.1	5.4	+1.3 (+32%)

Table 6. Modeled 2009 and 2010 season-mean (April 11 – October 3) energy balance components from Agro-IBIS simulations with live and dead *P. australis*, as well as the difference (dead minus live; also expressed as a percent change, in parentheses). Also shown in the right column is the observed difference (2010 minus 2009). Asterisks denote instances where the seasonal mean differences exceed instrument uncertainty bounds, while the † symbol indicates differences that are statistically significant, based on Student’s t-test ($p < 0.05$).

	2009 Modeled			2010 Modeled			Observations
	Live	Dead	Difference	Live	Dead	Difference	Difference
<i>Rn</i>	146	144	-2.8 (-2%)	155	153	-2.5 (-2%)	+4.3 (+3%)
<i>LE</i>	122	82.7	-39.5(-32%)	127	87.3	-39.2 (-31%)	-39.6 (-32%) [†]
<i>H</i>	23.9	57.8	+33.9 (+142%)	26.3	59.9	+33.6 (+128%)	+43 (+131%) * [†]
$\Delta S/\Delta t$	0.3	3.1	+2.8 (+930%)	2.3	5.4	+3.1 (135%)	+1.0 (32%) [†]

Table 7. Season-mean (April 11 – October 3) latent heat flux (W m^{-2}), season-total evapotranspiration (mm), and estimated water “savings” that resulted from the application of herbicide to the *P. australis*, based both on the Agro-IBIS model simulations and the observed energy balance. Model results are shown as the average of 2009 and 2010 simulations (e.g., “live” results are the average of the 2009-live and 2010-live simulations).

	<i>LE</i> (W m^{-2})	Total ET (mm)	Water “savings” (live – dead; mm)
Modeled live <i>P. australis</i> (2009-2010 mean)	124	771	244 mm (32% reduction in consumptive water use)
Modeled dead <i>P. australis</i> (2009-2010 mean)	85.0	527	
2009 observations (live)	124	770	245 mm (32% reduction in consumptive water use)
2010 observations (dead)	84.7	525

Figure 1. Map of wetland field site, adapted from Lenters et al. (2011), showing areas of wetland vegetation, as well as locations of both meteorological towers (purple dots) and LAS transmitter and receiver (yellow triangles).

Figure 2. Photos of *P. australis* at the wetland field site on July 21, 2009 (left panel) and June 14, 2010 (right panel). Viewpoint is looking east from the meteorological tower in the P section of the wetland.

a) Sensible heat flux

b) Latent Heat Flux

Figure 3. 5-day running mean observed energy balance components in the *P. australis* section of the wetland for 2009 and 2010, including: a) sensible heat flux, b) latent heat flux, and c) Bowen ratio (ratio of 5-day H to 5-day LE). Error bars in panel b) represent the maximum potential uncertainty in LE due to observational error in other measurements.

Figure 4. Mean diurnal energy balance components from 2009 and 2010 observations, averaged over the time periods indicated in each panel. Energy balance terms include net radiation (Rn), sensible heat flux (H), heat storage rate ($\Delta S/\Delta t$), and latent heat flux (LE), all in units of W m^{-2} . Error bars for LE represent the maximum potential uncertainty in latent heat flux due to observational error in other measurements.

Figure 5. Daily cumulative heat storage in the P section of the wetland (water column only), based on 2009 (gray) and 2010 (black) observations.

Figure 6. 5-day running mean observed energy balance components for 2010 in the P section of the wetland. Terms include net radiation (Rn), sensible heat flux (H), heat storage rate ($\Delta S/\Delta t$), and latent heat flux (LE) (also presented as ET in mm day⁻¹ on the secondary y-axis). Gray error bars for LE represent the maximum potential uncertainty in latent heat flux due to observational error in other measurements.

a) Latent heat flux

b) Sensible heat flux

Figure 7. Observed (solid) and Agro-IBIS modeled (dashed) values of a) latent heat flux and b) sensible heat flux for the 2009 (grey) and 2010 (black) growing seasons. Model results are shown for the 2009-real and 2010-dead simulations (i.e., the “validation” runs).

Figure 8. Agro-IBIS modeled partitioning of ET into evaporation (E) and transpiration (T), averaged over the 2009-2010 growing seasons and shown for conditions of live *P. australis* vegetation. Simulated ET in the presence of dead vegetation is also shown (E only; dotted line). Secondary y-axis displays water balance components in units of mm day⁻¹. Modeled LAI (solid line) and observed LAI (black dots) are also plotted, with values shown on the right y-axis.