Impact of rice cultivation on evapotranspiration in small seasonal wetlands of north-central Namibia

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Abstract:

This paper aims to evaluate the effect of mixed-cropping of rice and upland crops on evapotranspiration (ET) in a small seasonal wetland in the north-central Namibia. Meteorological observations were conducted in the experimental sloped field, which simulated the cultivation of both rice in a wetland environment and upland crops in the surrounding rain-fed area, and included a reference wetland with natural vegetation. During cultivation, ET from the rice field was similar to that from the wetland. However, during the dry period ET was remarkably reduced in the post-harvest field, while continuous ET occurred in the natural wetland even after surface water had dried up. The response of surface conductance to meteorological variables was investigated by means of the Jarvis–Stewart conductance model. During cultivation, surface conductance of the rice field and the wetland had a distinct stress response compared to that of the rain-fed crop field. During the dry period, surface conductance of the wetland site, in which the surface water dried-up, still responded to the meteorological conditions in contrast to those of the post-harvest field with plowed bare soil.

KEYWORDS evapotranspiration; surface conductance; surface water; seasonal wetland; rice and upland crops; north-central Namibia

INTRODUCTION

Large variability in precipitation is unavoidable in arid and semi-arid regions. Highly variable surface–water conditions year-to-year could threaten human activities, for example, crop production which relies on rain water (e.g. Dai, 2013; Kundzewicz et al., 2014). North-central Namibia, where the precipitation that occurs during the limited months of the wet season provides important water resources, faces both extreme droughts and floods (New et al., 2006; Persendt et al., 2015). During the wet season, however, local rainfall and floodwater from the Angolan highlands form a seasonal wetlands network covering a vast area of 800,000 ha, known as the Cuvelai system seasonal wetlands (Mendelsohn and Weber, 2011). Effective and sustainable land use and agricultural methods are required to adapt to the unstable and unpredictable variability in available water in this region (Niipele et al., 2015). To cope with both yearly and seasonally varying coverage of surface water, mixed cropping of flood-tolerant rice and drought–tolerant crops are promoted (Awala et al., 2016; Iijima et al., 2016).

Land–use change from natural vegetation to agricultural fields affects water resources including both ground and surface water, by modifying the surface water balance. Advanced assessment of the effects of introducing a mixed-cropping of rice and upland crops on evapotranspiration (ET) in the region is urgently needed (Hiyama et al., 2014). The introduction of rice in shallow water channels (iishana) has previously been investigated, revealing that rice cultivation reduces water loss to the atmosphere (i.e. evaporation) and enhances the conservation of surface water, when compared to a cultivated wetland with natural vegetation (Suzuki et al., 2014). Furthermore, considering the yearly variability around iishana, more reliable water availability is expected for the small seasonal wetlands (oondome) which are formed sporadically on slightly elevated areas between the shallow water channels, with the water traditionally being utilized for grazing and fishing (Niipele et al., 2015). Since the surface water of such small wetlands is important for both direct exploitation of the surface water and for underground water storage (Hiyama et al., 2017), the effect of agricultural use on water availability is critical to regional water cycles.

To evaluate ET from a vegetated field, the Penman–Monteith (P–M) equation is broadly used for various vegetation types, such as cropland, grassland, and forest (e.g. Allen et al., 2006; Katerji and Rana, 2006). Application of this model to wetland ecosystems has also been explored (e.g. Mohamed et al., 2012). Surface conductance (Gs), which is one of the important parameters in the big leaf concept of the P–M equation (Euguster et al., 2000), represents the bulk surface response due to physiological effects of plant stomata and physical effects of soil water availability when soil evaporation is negligible.
The aim of this study is to understand the effect of agricultural usage of small seasonal wetlands on ET. Here, we used meteorological observations and the Jarvis–Stewart type surface conductance model to investigate whether ET would increase or decrease, and if the response of \( G \) to environmental stress would change, following the introduction of rice-based mixed cropping in a small seasonal wetland of north-central Namibia.

**METHODS**

**Experiment sites**

The field experiment was conducted at the Ogongo Campus of the University of Namibia, in the Omusati region of Namibia (17°40'S, 15°17'E, and 1100 m above mean sea level) (Suzuki et al., 2014). The climate of the region is semi-arid with a mean annual temperature of 22°C and an annual precipitation of 400–450 mm (Awala et al., 2016). Clearly, seasonal precipitation, which is usually concentrated from mid–November to mid–April, distinguishes the wet and dry periods, both of which were observed during the study period (Figure S1). The study period covered years with relatively low rainfall, including a record drought during the wet season of 2012–13 (World Meteorological Organization, 2015).

To simulate cultivation in small, seasonal wetlands, an experimental field was set up 80 × 160 m in size with an artificial slope of 1/80 (Awala et al., 2013). By controlling the water level, the surface water was expanded to the middle part of the field, creating three types of surface conditions with different cultivation. Rice was planted in the inundated, lower part of the slope (site L) imitating a small wetland, while the upper part of the slope that lacked surface water (site U) was used for a mixed-cropping of pearl millet and cowpea. In the transition zone between sites L and U (site T), a close mixed-cropping (Awala et al., 2016; Iijima et al., 2016) of rice and upland crops, such as pearl millet and sorghum was tested. The rate of the mixed-cropping at both sites U (pearl millet and cowpea) and T (rice and upland crops) was 1:1 through the experiment years. The cultivation periods for each site/year can be found in Figure S2. Furthermore, a small wetland reference site (site W) was created by irrigation of natural herbaceous vegetation (e.g. gramineous plants and sedge) located 50 m from the edge of the sloped field. The locations and pictures of these test sites are provided in Figure S3. Variation in the PAI (plant area index) at each site is shown in Figure S4.

**Observation**

Meteorological observations were conducted at the sloped field and the reference wetland site. The observations commenced in September 2012 at sites L and U, January 2013 at site T, and September 2013 at site W. Here, we used data obtained until the end of August 2016. Details of the observations are provided in Text S1 and Table S1. The ET was calculated using the Bowen ratio energy balance (BREB) method (Bowen, 1926). The Bowen ratio was determined with two level observations of the air temperature and humidity (Table S1), and was used to partition available energy into sensible and latent heat fluxes. The available energy contains net radiation flux, ground heat flux, and the change in energy storage into a water body (Suzuki et al., 2014). The valid data for calculating ET and \( G \) were filtered (Text S2). Then, to evaluate seasonal variation and integration of evapotranspiration, any unavailable Bowen ratios were filled with the valid values at the same time in a day, averaged during a 7-day period (3-days before and after the target date) and the heat fluxes were calculated.

The \( G \) was calculated via the P–M equation (Monteith, 1965) using the latent heat flux (i.e. ET) and meteorological variables. The aerodynamic conductance required in the P–M equation was derived assuming the logarithmic law of wind speed with the roughness length and displacement height, which were estimated via parameterization with the plant height (e.g. Brutsaert, 1982). Details of the parameters used in this calculation are given in Text S3.

**Surface conductance model**

To investigate the response of \( G \) on environmental variables, observational data were applied to the Jarvis–Stewart (J–S) type conductance model, in which the maximum values of \( G \) (\( G_{\text{max}} \)) that is unaffected by environmental stresses is reduced by an amount equivalent to the environmental stress. This model was originally developed for leaf stomata (Jarvis, 1976) and applied to the canopy scale (Stewart, 1988). While several variations of the stress functions have been proposed (Wang et al., 2014), we used the functions of solar radiation \( S \), vapor pressure deficit \( D \) (hereafter humidity deficit), and air temperature \( T \) from the study conducted by Matsumoto et al. (2008). The function of volumetric soil water content \( \theta \) was modified as a sigmoid function to present non-zero conductance under reduced surface soil water, considering the available water from the deeper soil. The J–S type conductance model is given as Equation (1) with the environmental stress functions \( f_i - f_s \), which take values from 0 to 1.

\[
G_s = G_{\text{max}} f_1(S) f_2(D) f_3(T) f_4(\theta) \tag{1}
\]

We optimized the conductance model with observation datasets for each site and period (cultivation and dry periods shown in Figure S2). Details of the stress functions and the methods of evaluating the model are described in Text S4.

**RESULTS AND DISCUSSION**

**Seasonal and annual evapotranspiration**

Seasonal variations in the ET and \( G \) show variability among the sites and years (Figure 1). Generally, ET and \( G \) were close to zero during the dry period, and they increased following the onset of the wet season. The difference between the sites during the cultivation period mostly depended on the surface water conditions. The lowest values for ET and \( G \) were observed at site U, and the opposite was true for sites L and W. Yearly variation in ET and \( G \) during the cultivation period at site L was small compared to those for site U and T, which followed yearly variation of PAI (Figure S4). As the dry period commenced, a rapid decrease in ET and \( G \) values was observed at the three
crop sites where the tilling process to a soil depth of <15 cm after harvest resulted in discontinuous capillary channels and reduced water vapor transport inside the soils (e.g. Schillinger and Bolton, 1993). A sudden increase in ET and \( G_s \) in July or August in the cropped field was caused by plowing. In contrast, ET at site W did not decrease at the onset of the dry period and, in fact, formed a second peak due to the remaining surface water in 2014 and 2015. Even after surface water disappeared and grass plants began to wither, relatively higher ET and \( G_s \) values were observed at site W, compared with the cropped field. Standing dead plants possibly acted as transport pathways of liquid water via capillary action or water vapor diffusion from deeper layers in the soil, supporting evaporation when the dry surface soil layer formed.

The mean (maximum) values of daily ET during the cultivation period were 1.4 (5.4), 2.5 (9.0), 3.4 (11.2), 3.8 (10.3) mm d\(^{-1}\) at sites U, T, L, and W, respectively. ET at site U was about half that at other sites. The mean values of daily ET during the dry period was 0.6, 0.8, 1.0, and 2.5 mm d\(^{-1}\) at sites U, T, L, and W, respectively, and distinct differences were found between the values for dried-up wetland and the other three crop sites. The annual integration of ET and precipitation calculated in a hydrological year (from September to August) are shown in Figure 2. The annual ET varied from 266 to 424 mm at site U, from 438 to 666 mm at site T, from 647 to 779 mm at site L (1025 mm in 2012–13 with irrigation test before cultivation), and from 974 to 1166 mm at site W. The annual precipitation was 285–415 mm, which is comparable to the annual ET of the rain-fed site U. The annual ET at the rice-cropped sites reduced to 60% of the ET occurring in the reference wetland in 2015–16, during which surface water was present in approximately the same time periods at sites L and W (Figure 1). This difference in annual ET was produced during the dry period, in which ET over the bare land (after harvesting the cropped field) reduced quickly compared to those over the dried-up wetland.

**Application of surface conductance model**

Stress functions with optimized parameters in Table I and relationships between \( G_s/G_{s,max} \) and stress variables (\( S, D, T, \) and \( \theta \)) are shown in Figure 3 (cultivation period) and Figure 4 (dry period). Differences in \( G_{s,max} \) among sites corresponded to the presence of surface water, rather than to the difference in PAI (Figure S4). PAI of rice in site L, in which the largest \( G_{s,max} \) was found, was not always larger than the upland crops (site U) or the mixed-cropping rice...
and upland crops (site T). On the contrary, site U, which was not affected by surface water, had a $G_{s,max}$ that was an order of magnitude lower than that of the other three sites, where the range of $G_{s,max}$ was similar to those previously obtained for cropped fields and grasslands (e.g. Kelliher et al., 1995; Alfieri et al., 2008). During the dry period, the differences in $G_{s,max}$ among the sites reduced. The highest $G_{s,max}$ value was obtained at site W. The three cropped sites, where the whole area was cleared after harvest, had similar magnitudes of $G_{s,max}$.

Differences in the optimized stress functions among the sites were found during the cultivation period. Relatively linear responses to solar radiation were found at sites L and W, while an asymptotic response, in which restriction by temperature likely had a smaller effect compared with the other stress variables. Previous studies (e.g. Sellers et al., 1997; Harris et al., 2004) also found that the optimum temperature ($T_{opt}$) is approximately equal to the annual mean temperature, and the period in which temperature restricts the conductance is not long. However, since the temperature range during cultivation was small (< 20°C), the temperature range over which the plants responded was likely not covered in our experiment (Wright et al., 1995).

Soil water function ($f_2$) varied among the sites (Figure 3d). During the cultivation period of 2013, the surface soil became extremely dry ($\theta < 0.2$). While the upper limit of $G_s/G_{s,max}$ at site T was <0.2, that at site U remained at 0.4. The dryness tolerance of pearl millet and cowpea (e.g. Petrie and Hall, 1992) and the possibility of plant water uptake in deeper soil layers are considered as a reason for the relatively large $G_s$ at site U. At site L, a large $G_s/G_{s,max}$ was obtained and was probably due to sufficient soil water retained in the deeper soil layers after drainage of irrigation water. Although a similar situation is possible at site W, it is difficult to compare this reference site with the other sites because of a lack of observations of the reduced soil water conditions in 2013 at site W. In this study, sustained $G_s$ even with surface soil water close to zero, was presented by...
introducing the sigmoid function.

During the dry period, the differences in the stress functions among the sites reduced compared with that in the cultivation period (Figure 4). Nonetheless, the dried-up wetland was distinguished from the other sites, particularly for the solar radiation and air humidity deficit (Figure 4a and 4b). Over a soil surface without active vegetation, environmental stress that directly affects the $G_s$ is primarily due to soil water deficit. Under high solar radiation and/or air humidity deficit, $G_s$ was abruptly reduced in the cropped field (Figure S5) probably because of a deficit in soil water under high evaporative demand. In contrast, such a reduction in $G_s$ at high solar radiation and air humidity deficit was not observed at site W, in which continuous evaporation might have been possible during the dry period, as discussed above. This difference in $G_s$ behavior should result in differences in the stress functions.

The root-mean square error (RMSE) and mean bias error (MBE) of ET, calculated by validating the dataset using the P–M equation and the optimized conductance model, are shown in Table SII. RMSEs of ET were 2.3–4.6 mm d$^{-1}$ for the cultivation period and 1.8–3.4 mm d$^{-1}$ for the dry period. The conductance model overestimated $G_s$ to the same order of magnitude as the observations (Table SII). Overestimation of $G_s$ might originate from formation of the conductance model (Equation 1). Since $G_{s,max}$ is multiplied by the stress function within the range 0–1, it is difficult to reduce the value by several orders of magnitude. However, ET based on the P–M equation has only a small sensitivity to $G_s$ but a large dependency on the available energy because of the small aerodynamic coupling of the herbaceous canopy to the atmosphere (Kelliher et al., 1993; Kumagai, 2011). The decoupling factors (Jarvis and McNaughton, 1986) averaged during the cultivation period were 0.39, 0.49, 0.68, and 0.62 at sites U, T, L, and W, respectively, which was within the typical range for agricultural fields. Therefore, the estimation error of $G_s$ did not strongly affect the value of ET.

**CONCLUSIONS**

Rice cropping in the seasonal wetlands of north-central Namibia resulted in ET during cultivation similar to that of an uncultivated wetland with natural vegetation. After surface water disappeared in the dry period, the plowed land surface dried out and evaporation decreased rapidly compared with the naturally vegetated wetland. Rice cultivation with a plant density similar to this study would decrease the annual ET in a small seasonal wetland in this region. To minimize changes in the water budget as much as possible, effective treatment of the bare surfaces after harvest may need to be considered. The $G_s$ and its response to environmental stress varied among the sites and were affected mostly by the availability of surface water. The presence of surface water resulted in a large $G_{s,max}$ and an obscured contribution of stomatal response. The stress response to an air humidity deficit and soil water varies among the different vegetation cover. During the dry period, the stress functions at the naturally vegetated wetland were distinct from the plowed crop fields. Effects of land use remained in terms of the behavior of $G_s$ throughout the year.
EVAPOTRANSPIRATION IN WETLAND RICE FIELD

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SUPPLEMENTS

Figure S1. Seasonal variations in (a) daily mean solar radiation \( (S) \), air temperature \( (T) \), and precipitation, and (b) specific humidity \( (q) \) at the study site.

Figure S2. Cultivation periods of the experimental field. Solid and dashed lines indicate the cultivation period and the dry (non-cultivation) period, respectively. Thin lines and dates in parentheses under site L show periods of irrigation.

Figure S3. (a) Location of the experimental field. Black squares indicate the positions of the observation points (not to scale). The shaded area indicates the maximum surface water coverage. Photograph of (b) site U (February 1, 2017), (c) sites T and L (April 13, 2013), (d) site W (March 13, 2015), (e) site T (August 31, 2016), and (f) site W (August 31, 2016).

Figure S4. Seasonal variation in the plant area index showing mean values from 4 measurements with standard deviations (error bars) at each site. Evaluation of values at sites U and T were based on both crops in the mixed-cropping (pearl millet and cowpea at site U, and rice and upland crops at site T). Only mean values were obtained for 2013. Rice at sites L and T was submerged by the irrigation water in the middle of February 2014.

Figure S5. Relationships between surface conductance and four environmental variables during the dry periods: (a) solar radiation, (b) vapor pressure deficit, (c) air temperature, and (d) volumetric soil water content. Graphs of four sites are drawn separately in orange, green, blue, and cyan for sites U, T, L, and W, respectively.

Table S1. List of observation instruments.

Table SII. Root mean square error (RMSE) and mean bias errors (MBE) of estimated evapotranspiration and surface conductance.

Text S1. Observation in the experimental sloped field.

Text S2. Strategy of filtering valid data.

Text S3. Evaluation of surface conductance.

Text S4. Application of the surface conductance model.

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