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Actual evapotranspiration and dual crop coefficients for dry-seeded rice and hybrid maize grown with overhead sprinkler irrigation

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ABSTRACT

In lieu of the decreasing availability of water for irrigated rice, we examined two alternatives to traditional rice cultivation on puddled and saturated soil–maize and dry-seeded rice production grown with an overhead sprinkler irrigation system. We characterized the inter-seasonal daily variations of actual crop evapotranspiration (ET), transpiration (*T*), and evaporation (*E*) using the eddy covariance (EC) technique during 2011 and 2012 dry seasons. The average growing season ET rate of maize was 3.90 mm d^{-1} in 2011 and 3.74 mm d^{-1} in 2012. For the dry-seeded rice, the average growing season ET rate was 4.36 mm d^{-1} in 2011 and 4.13 mm d^{-1} in 2012. Growing season ET of maize (484 mm) and dry-seeded rice (523 mm) in 2011 were higher than during 2012 (453 mm for maize and 475 mm for dry-seeded rice) because of higher net radiation (R_n) in 2011. Partitioning ET showed that *T* accounted for 66–74% of seasonal ET for maize and 53–60% for dry-seeded rice. On average, dry-seeded rice had 6.5% more ET than maize due to higher irrigation water inputs. The average total water input (irrigation + precipitation) for maize was 618 mm while that of the dry-seeded rice was 908 mm. The large difference between crop coefficient (K_c) and basal crop coefficient (K_{cb}) values during the initial and crop development stages of both maize and dry-seeded rice provides a good opportunity to optimize irrigation water input by designing a more efficient irrigation schedule that is appropriate to the water needs of the crops.

1. Introduction

Worldwide, water for agriculture is becoming increasingly scarce as competition between industrial, municipal, and environmental users of water grows and due to decreasing resources as climatic variability increases (Rijsberman, 2006). By 2025, 15–20 million hectares of irrigated rice in Asia may suffer from water scarcity (Tuong and Bouman, 2003). The decreasing availability of water for irrigated rice threatens food security in Asia in general and the livelihood of farmers in particular. Interventions to respond to water scarcity imply a reduced use of irrigation water or a diversification to other more water-efficient crops. One alternative is dry-seeding of rice without prior soil saturation, which has been practiced historically in rainfed and deepwater rice ecosystems (De Datta, 1986) and offers potential in irrigated environments with limited water. The diversification of rice to maize production is also gaining importance on lowland soils across tropical and subtropical Asia in response to the increasing demand of maize for feed and biofuel (Timsina et al., 2011). To better manage irrigation water inputs and improve water use efficiency for dry-seeded rice and maize production, it is essential to understand the actual crop evapotranspiration (ET) and the dual crop coefficients ($K_{cb} + K_e$).

In 2011, we started to monitor the fluxes of water vapor and CO_2 using the eddy covariance (EC) technique in both maize and dry-seeded rice fields under overhead sprinkler irrigation (Alberto et al., 2013). The EC method provides a direct measurement of actual crop evapotranspiration (ET), where fast fluctuations of vertical wind speed are correlated with those in water vapor density (Shuttleworth, 2007; Drexler et al., 2004; Allen et al., 1998). Evapotranspiration can be measured using devices such as lysimeters but it can also be estimated using hydrological, micrometeorological and plant physiological approaches (Rana and Katerji, 2000). However, the EC technique, recognized as the standard micrometeorological method to measure ET, can accurately capture ET information over a large area (Baldocchi, 2003). Evapotranspiration is an important part of the field water cycle and has significant influences on crop growth, development and yield. Actual ET reflects the crop's water need which consists of transpiration (*T*) and

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evaporation (E). The crop coefficient (K_c) can likewise be determined by dividing ET with ET_o (reference crop evapotranspiration) provided the crop is unstressed (Allen et al., 1998). Determination of K_c under local climatic condition is the basis to improve planning and efficient irrigation management in many field crops (Kang et al., 2002; Sepaskhan and Andam, 2001). However, previous studies mainly concentrated on K_c, but paid little attention to its components: K_{cb} (basal crop coefficient) and K_e (soil water evaporation coefficient). In the dual crop coefficient approach, the effects of crop transpiration and soil evaporation are determined separately. Thus, K_c is further split into K_{cb}, to describe plant transpiration, and to K_e, to describe evaporation from the soil surface. Accurate measurement of ET and the determination of the dual crop coefficients ($K_{cb} + K_e$) will help further reduce irrigation water input and can improve crop water use efficiency, which is drawing more attention in view of potential future shortages of water needed for agricultural production.

Few studies on dry-seeded rice have reported ET values derived from water-balance equation (Sudhir-Yadav et al., 2011; Singh et al., 2006; Cabangon et al., 2002), and ET values measured using lysimeter (Roel et al., 1999); but none on ET values obtained from EC measurements. We have, however, investigated the energy exchanges of flooded and aerobic rice fields from 2008 to 2009 (Alberto et al., 2011, 2009). Several studies on maize ET estimated by EC method in temperate countries have already been reported (Ding et al., 2010; Lei and Yang, 2010; Suyker and Verma, 2010, 2009, 2008; Li et al., 2009, 2008; Tong et al., 2009); but none on irrigated maize in the tropics.

In this paper, we examine two alternatives to traditional rice cultivation on puddled and saturated soil–maize and dry-seeded rice. Our objectives are to characterize the inter-seasonal variations of ET and its components in maize and dry-seeded rice fields using the EC technique and to derive the dual crop coefficients for both crops. We examine environmental and biophysical factors that affect these variations. This baseline information can be used to design more efficient irrigation scheduling to optimize crop water productivity for both dry-seeded rice and hybrid maize grown under overhead sprinkler irrigation systems in the tropics. We present results for both crops during two contrasting dry seasons (DS), from January to May, in 2011 and 2012.

2. Materials and methods

2.1. Site description

The study sites are located within the Experimental Station of the International Rice Research Institute (IRRI) in Los Baños, Laguna, The Philippines, about 66 km south of Manila (Alberto et al., 2013). The site has a slope of 1% with northeasterly aspect, and an elevation of 27 m above sea level. The soils are Lithic Haplustept (Soil Survey Staff, 2010) varying in texture from loam to clay and overlying volcanic tuff evident at 0.3 m to 1.2 m depth. One site (Block UE: 14°8′ 49.72″ N, 121°15′58.10″ E) was planted with maize during 2011 and dry-seeded with rice during 2012. The second site (Block UJ: 14°18′43.26″ N, 121°15′54.94″ E) was dry-seeded with rice during 2011 and planted with maize during 2012. The two sites were each 4 ha (200 m × 200 m) with a 103-m length center pivot, overhead sprinkler irrigation system and an EC system placed at the center. The area provided sufficient upwind fetch of uniform cover required for adequately measuring mass and energy fluxes using the EC systems. There were no obstructing buildings on both the windward and leeward sides.

Both sites were historically cropped with paddy rice prior to the installation of the overhead sprinkler irrigation systems. At the start of each season, both sites were uniformly tilled by disk plowing and rotavation, which incorporated weed biomass and residues from the previous rice crop, and the fields were laser leveled.

The rice variety in each season was NSIC Rc 222, a semi-dwarf, high yielding lowland irrigated variety (PhilRice, 2010). Rice was dry-seeded with a tyne planter at 20-cm row spacing and 50–60 kg seed ha^{-1} on 29–30 January in 2011 and 40–45 kg seed ha^{-1} on 25–27 January in 2012. Fertilizers were applied basally at 40 kg N ha^{-1}, 17 kg P ha^{-1}, and 33 kg K ha^{-1} as granular fertilizers within the seed row; additional urea fertilizer was broadcast in four splits totaling 150 kg N ha^{-1} in 2011. In 2012, fertilizers were applied basally at 32 kg N ha^{-1}, 14 kg P ha^{-1}, 27 kg K ha^{-1} as granular fertilizers within the seed row; additional urea fertilizer was applied using fertigation (with 4 mm applied water) in five splits totaling 150 kg N ha^{-1}.

Maize in each season was Pioneer hybrid 30T80. Maize was sown with a disk planter at 60-cm row spacing and 70,000 seeds ha^{-1} on 15–21 January in 2011 and 75,000 seeds ha^{-1} on 21–22 January in 2012. Granular fertilizer was banded basally at 56 kg N ha^{-1}, 24 kg P ha^{-1}, 47 kg K ha^{-1} at a depth of 10 cm and offset by 10 cm from the seed row; additional urea fertilizer was broadcast in two splits totaling 164 kg N ha^{-1} in 2011. In 2012, granular fertilizer was banded basally at 24 kg N ha^{-1}, 10 kg P ha^{-1}, 20 kg K ha^{-1} at a depth of 10 cm and offset by 10 cm from the seed row; additional urea fertilizer was applied using fertigation (with 4 mm applied water) in five splits totaling 180 kg N ha^{-1}.

Irrigation scheduling was managed to ensure that adequate water was applied to provide a non-limiting environment for optimal crop growth. For each crop, irrigation water was applied using a Zimmatic® center pivot (Lindsay Corporation, Australia), 103-m in length with the end guns removed. Irrigation scheduling was based on the average soil water potential (SWP) readings of eight tensiometers distributed in each study site. Irrigation was applied when the average SWP readings reached −10 kPa at 15-cm depth for dry-seeded rice and −50 kPa at 40-cm depth for maize. The cumulative crop evapotranspiration and rainfall were used to determine the amount of water applied at each irrigation event, which varied from 10 to 24 mm. Crop evapotranspiration (ET) was calculated using data collected from the EC systems at the center of each field. The irrigation water comes from deep wells pumped into a reservoir, which contains low levels of bicarbonates and nitrates (pH: 7.98; EC: 0.75 dS m^{-1}; HCO_3^-: 0.00538 mol L^{-1}; NO_3^--N: <0.1 mg N L^{-1}). Fig. 1(a–d) shows the occurrence of precipitation and irrigation events as well as groundwater levels during the cropping seasons for both maize and dry-seeded rice.

2.2. Measurement of fluxes, microclimate and plant parameters

Fluxes of CO_2, latent heat (LE), and sensible heat (H) over the plant canopy were measured by the EC technique (Alberto et al., 2013, 2012, 2011, 2009). A sonic anemometer–thermometer (CSAT3, Campbell Scientific, Inc., USA) measured three dimensional wind speed and sonic or virtual temperature. An open-path infrared analyzer (LI-7500, LI-COR Inc., Lincoln, NE, USA) measured fluctuations in CO_2 and water vapor densities. Both sensors, CSAT3 and LI-7500, were installed on an aluminum tripod mast with a sensor separation of about 20 cm. The LI-7500 was set back from the CSAT3 to minimize flow distortions, and the head was tilted about 15° from vertical to minimize the amount of precipitation that accumulated on its window. To have sufficient fetch representative of the sites being studied, the EC sensors were mounted 2 m above the ground when the maize plants were shorter than 1 m and later raised to a height of 3 m until harvest; for rice, the sensor height was fixed at 2 m. The data from CSAT3 and LI7500 were sampled at 10 Hz using a data logger (CR3000, Campbell Scientific, Inc., USA). The EC raw data were processed and quality controlled (tests according to Foken et al., 2004) using EddyPro Express software (LI-COR Inc.,