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Carbon uptake and water productivity for dry-seeded rice and hybrid maize grown with overhead sprinkler irrigation

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ABSTRACT

A growing scarcity of irrigation water could progressively lead to changes in rice production to systems using less irrigation water for rice or more crop diversification. A shift from current production of rice on flooded soils to production of rice on non-flooded soil with water-saving irrigation or to production of more water-efficient crops will have profound effects on carbon, water, and energy exchanges. This study used the eddy covariance technique to examine C uptake and water use efficiencies for water-saving, dry-seeded rice production and production of hybrid maize under overhead sprinkler irrigation as an alternative to flooded rice during two growing seasons. Maize with its C_4 physiology has greater photosynthetic capacity than rice. In 2011, maize had 1.4 times higher net C uptake than rice and twice as much grain yield as rice (10.4 vs 5.3 Mg ha^{-1}). In 2012, lower solar radiation due to increased cloudiness and heavy rainfall during critical growth stages (late vegetative to early reproductive) decreased LAI and resulted to about 20% less net C uptake and maize yield (8.2 Mg ha^{-1}), but the rice yield was unchanged (5.3 Mg ha^{-1}) presumably because of improved crop management which included effective crop establishment at lower seed rate and efficient N application using fertigation. Canopy light use efficiency, crop water productivity (WP_{ET}), and photosynthetic water use efficiency were 1.8, 1.9, and 1.6 times higher for maize than rice, respectively, despite sensitivity of maize to excess water. Net C uptake, evapotranspiration, and WP_{ET} of dry-seeded rice under overhead sprinkler irrigation were comparable to those reported elsewhere for flooded rice. Average total water input (irrigation + rainfall) for rice was only 908 mm, as compared to 1300–1500 mm reported in literature for typical puddled transplanted rice.

1. Introduction

Water scarcity occurs with increasing frequency in many regions of the world as competition between industrial, municipal, agricultural, and environmental (i.e., to create and maintain wildlife habitat) users of water resources grows and climatic variability increases (Hanjar and Quereshi, 2010; Hoekstra et al., 2012). The growing scarcity of water worldwide has already started to influence conventional irrigated rice production. By 2025, a "physical water scarcity" might be confronted in 2 Mha of irrigated dry season rice and 13 Mha of irrigated wet season rice in Asia as supplies for irrigation dry up (Tuong and Bouman, 2003). An additional 22 Mha of irrigated dry season rice in South and Southeast Asia might face "economic water scarcity" as increasing costs for irrigation become too high for rice farmers (Bouman et al., 2005). Rice production must increase with less irrigation water or with diversification to other more water-efficient crops. Asian farmers with two rice crops per year could convert to a single rice crop in the wet season followed by a rainfed crop species with lower water demand in the dry season as supply of irrigation water decreases.

The rice–maize cropping system is gaining importance on flooded soils across tropical and subtropical Asia in response to the increasing demand of maize for feed and biofuel (Timsina et al., 2011). Both rice and maize can be typically grown with irrigation in the dry season. Rice is well adapted to wet seasons, where rain often exceeds evapotranspiration, but rains and water logging in the wet season can constrain maize production on paddy soils. Thus, rice in the wet season and maize in the dry season can provide a high-yielding, water-saving alternative to rice–rice cropping.

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Rice in Asia is typically grown on puddled and submerged soils. Soils are typically flooded and saturated before tillage. Subsequent tillage of saturated soil, referred to as puddling, creates a favorable environment for water retention and establishment of rice by transplanting or direct seeding of germinated seeds (wet seeded rice). This process of puddling can consume considerable water (Bouman and Tuong, 2001). A water-saving 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. Additional water can be saved by growing the dry-seeded rice on non-saturated rather than saturated soil; but this method of rice cultivation sometimes referred to as aerobic rice can lead to yield losses for rice (Tuong and Bouman, 2003). Dry-seeded rice grown without prior soil saturation as a water-saving technology could be attractive to Asian farmers favoring production of rice rather than other crops as a means to ensure food security.

This shift from traditional rice cultivation with puddled and submerged soil to water-saving rice cultivation practices without soil puddling and diversified cropping systems with less rice will reduce duration and frequency of soil submergence and associated anaerobic soil conditions. This can have profound effects on carbon (C) and nitrogen (N) budgets of rice fields (Bronson et al., 1997a,b; Abao et al., 2000; Wassmann et al., 2000). The shift can also affect the water and energy exchanges in the rice production systems. Changing agricultural practices has been shown to affect local energy, water, and carbon balances in agricultural fields (Zhao et al., 2008; Sakai et al., 2004). The underlying processes and short and long-term effects of such changes must be understood in order to formulate appropriate management strategies that will ensure the sustainability and productivity of these ecosystems.

Several studies have already been conducted on the energy and CO_2 exchanges of maize fields using the eddy covariance technique (EC) in temperate countries (Bai et al., 2012; Hernandez-Ramirez et al., 2011; Ji et al., 2011a,b; Suyker and Verma, 2010, 2009, 2008; Wang et al., 2010; Arkebauer et al., 2009; Stella et al., 2009; Suyker et al., 2004, 2005; Verma et al., 2005); but none on irrigated maize after rice in the tropics. We have, however, investigated energy and CO_2 exchanges of flooded rice fields from 2008 to 2010 (Alberto et al., 2012, 2011, 2009).

In 2011, we started to monitor the fluxes of water vapor and CO_2 using the EC technique in both maize and rice fields under water-saving overhead sprinkler irrigation. In this paper, we examine two water-saving alternatives to traditional rice cultivation on puddled and saturated soil–maize and dry-seeded rice. Our objectives are to characterize the seasonal variations of CO_2 and water vapor exchange in maize and rice fields under overhead sprinkler irrigation in the tropics and to identify the environmental and biophysical factors affecting the C uptake and water productivity for the two crops. We present results for both crops in 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. The site has a slope of 1% with a 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. The topsoil (0-0.15 m) has a mean pH of 6.2 (1:1 soil/water suspension), organic carbon concentration of 1.1%, and cation exchange capacity of 27 $cmol_c\ kg^{-1}$. 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 100-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 disc 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 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 disc 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}; 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}.

For each crop, irrigation water was applied using a Zimmatic® center pivot, 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 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_c) was calculated using data collected from the eddy covariance 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; HCO_3^-: 0.00538 mol L^{-1}; NO_3^--N: <0.1 mg N L^{-1}).

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., 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