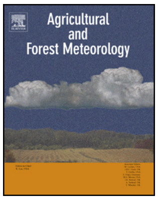
Agricultural and Forest Meteorology 228–229 (2016) 229–238

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Canopy scale CO_2 exchange and productivity of transplanted paddy and direct seeded rainfed rice production systems in S. Korea

Steve Lindner[a,*], Wei Xue[a], Bhone Nay-Htoon[b], Jinsil Choi[c], Yannic Ege[a], Nikolas Lichtenwald[a], Fabian Fischer[a], Jonghan Ko[c], John Tenhunen[a], Dennis Otieno[a]

[a] Plant Ecology, BayCEER, University of Bayreuth, Universitätsstraße 30, 95447 Bayreuth, Germany
[b] Agro-ecosystem Research, BayCEER, University of Bayreuth, Universitätsstraße 30, 95447 Bayreuth, Germany
[c] Applied Plant Science, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju 500-757, Republic of Korea

ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form 29 March 2016
Accepted 14 July 2016
Available online 22 July 2016

Keywords:
Agricultural crop
Ecosystem CO_2 exchange
Closed-chamber technique
Crop productivity
Biomass development
Gross primary production

ABSTRACT

Rice (*Oryza sativa* L.) is a primary food crop that supports more than half the world population. Paddy rice accounts for more than 75% of the total global rice production but requires large amounts of water for irrigation. Increasing water scarcity, however, raises concerns regarding the sustainability of paddy rice production and highlights the need for alternative approaches. Improved rice varieties that require less water, are drought tolerant and which can be directly seeded offer promising alternatives. In this study, we evaluated the performance of an improved rice variety (*Oryza sativa* subsp. Japonica cv. Unkwang) grown under direct seeding and rainfed cultivation. Aboveground biomass and leaf area development were measured every month by destructive harvesting. Canopy net ecosystem CO_2 exchange (NEE) and ecosystem respiration (R_{eco}) were measured using chambers. Gross primary production (GPP) was calculated from NEE and R_{eco}. The maximum green leaf area index (GLAI) attained under rainfed agriculture was $4.9 \pm 0.5\ \mathrm{m^2\,m^{-2}}$ compared to $5.4 \pm 1.1\ \mathrm{m^2\,m^{-2}}$ in the conventional paddy rice production system. The respective peak total aboveground biomasses were 2.16 ± 0.28 and $1.85 \pm 0.27\ \mathrm{kg\,m^{-2}}$ while the corresponding grain weights were $1.19 \pm 0.10\ \mathrm{kg\,m^{-2}}$ and 1.16 ± 0.09, amounting to total yields of 6.61 ± 0.22 and $5.99 \pm 0.68\ \mathrm{t/ha^{-1}}$ for paddy and rainfed rice, respectively. The maximum daily cumulative GPP were 11.1 and $12.0\ \mathrm{gC\,m^{-2}\,d^{-1}}$, respectively, occurring at peak season, corresponding to maximum photosynthetic active radiation (PAR) and GLAI. On a daily basis, PAR explained >82% of the daily fluctuations in GPP while >90% of the seasonal changes in GPP were due to changes in GLAI and light use efficiency (α). Higher α in rainfed rice was attributed to higher leaf nitrogen (N) content. With adequate soil moisture supply, the Unkwang variety demonstrated the potential to grow under rainfed agriculture with comparatively good amount of yield. Since direct seeding, as in rainfed agriculture, eliminates the need for prior flooding of plots, it maximizes the use of early rainfall, which could be a water saving strategy and a reason to promote the introduction of Unkwang variety in the paddy rice-dominated Asian farming system.

1. Introduction

Rice (*Oryza sativa* L.) is a primary food crop supporting more than half the world's population and covers about 150 million hectares of land (Bouman et al., 2007). Worldwide, most rice production is done through flooding or paddy cultivation (Barker et al., 1999). Increasing water scarcity due to droughts and competing demands for water resources (IPCC, 2008) from growing domestic and industrial uses however, threaten the current production practices, raising the need for alternative production approaches. In this regard, the development of improved varieties that require less water or are more drought tolerant has been promoted (Barker et al., 1999). The culture of direct-seeded rice grown in unsaturated soils is another promising way to reduce irrigation requirements by more than half, compared to the conventional paddy rice (IRRI, 2002; Kato et al., 2006a; Okami et al., 2013).

In paddy rice fields, the amount of water that directly supports production is the transpired water since it is directly linked to CO_2 uptake, plant growth and yield. The bulk of the water in the flooded field is not directly related to production and is

---

* Corresponding author.
E-mail addresses: SteveLindner@yahoo.de, linde4all2001@yahoo.de (S. Lindner).

http://dx.doi.org/10.1016/j.agrformet.2016.07.014
0168-1923/

either re-directed back to the streams, percolated or evaporated. Thus, production systems that only supply the evapotranspiration demands could be a big saving on water resources and are environmentally friendlier (Toung and Bouman, 2003). Dry-seeded, rainfed rice offers an alternative to rice farmers, especially in Asia, where paddy rice production is more or less cultural and does not accommodate alternative crops as a means of ensuring food security. Rainfed rice production is already being experimented in some parts of Asia as an alternative to the traditional paddy rice (Kato et al., 2006a). Although most results from these trials showed lower yields of between 20 and 30% caused by drought (Okami et al., 2013), there are indications that yields of up to 8–11 t ha^{-1} (typical of paddy rice) are tenable with proper management (Okami et al., 2013). The dry-seeded rainfed rice technology may thus offer an opportunity for rice production through efficient use of ambient rainfall.

The main challenge to rainfed rice production however, is to supply adequate water that replaces daily evapo-transpiration and ensuring that photosynthesis proceeds uninterrupted. High transpirational water demand that occurs almost on a daily basis during midday, when vapor pressure deficit (VPD) is high, potentially lowers production, since plants close their stomata in order to check runaway cavitation at the expense of CO_2 fixation (Sperry, 2000). On an annual basis, this could lead to a significant reduction in yield. Rainfed rice may improve water uptake through increased root biomass, or physiological adjustments by re-directing assimilates to the roots to increase the root osmoticum (Munns, 1988; Kato et al., 2007; Wada et al., 2014). In such cases however, resources that could be used in grain production are re-directed in order to increase the plant's water uptake capacity, potentially lowering yield.

While paddy rice may be spared such a reduction in productivity because it stands in saturated soil, it faces a different challenge that may also effectively reduce shoot water supply and result in water stress during the day. Flooding of paddy fields limits oxygen diffusion into the soil, creating an anoxic soil substrate. Plant roots must, therefore, rely on oxygen supply from the surface, transported by the aerenchyma to the root apex (Moog and Brüggemann, 1998; Busch, 2001; McDonald et al., 2002; Colmer et al., 2003). To minimize radial oxygen losses during transport, large sections of the roots are often suberized (i.e. deposition of suberin, a hydrophobic plant polymer, on the cell walls and in the intercellular space), effectively blocking water flow through the apoplast, such that the roots can no longer take part in water uptake. In this case, water uptake is restricted to the short, narrow portions near the root apex of the deep roots, which remain unsuberized (Ranathunge et al., 2004; Kotula et al., 2009). This must effectively lower the efficiency of water uptake in paddy rice and could result in transient water stress and stomatal closure during midday, when light conditions and temperature are most conducive for plant production. In this case, flooding may not offer any advantage to paddy rice, unless through the dampening the VPD above the canopy. Incorporating cultivars with efficient water and nutrient uptake and transport into the rainfed rice production offers an opportunity to respond to the challenges associated with rice production (Kato et al., 2006a).

In this study, we experimented on a new rice cultivar (*Oryza sativa* L. subsp. Japonica cv. Unkwang) that has been developed from a high yielding, cold tolerant and early maturing variety to accommodate the demands of the northern plains and mountainous areas of South Korea (Kim et al., 2006). The Unkwang rice variety was grown under both the rainfed and conventional paddy production systems for comparison. Our hypotheses were that under adequate soil moisture supply, the Unkwang rice grown in a rainfed system: a) maintains similar rates of CO_2 uptake and light use efficiencies compared to that in a paddy system, and b) does not alter C allocation patterns in comparison to the paddy condition. Under such circumstances we anticipated similarities in crop development and yield between rainfed and paddy rice.

Table 1
Field management of the study site in 2013 in Gwangju.

Event	Date Paddy Rice	Date Rainfed Rice
Plowing	10.05.13	17.04.13
Flooding	14.05.13	–
Herbicides application	16.05.13	–
Basal fertilization	19.05.13	22.04.13
Transplanting/Planting	20.05.13	22.04.13
Pesticides application	20.05.13	26.04.13
Herbicides application	–	06.05.13
Manual weeding	–	22.05.13
Herbicides application	–	25.05.13
Manual weeding	–	20.06.13
Supplemental fertilization	07.06.13	09.06.13
Harvest	07.10.13	10.10.13

2. Materials and methods

2.1. Study site

The study was conducted during the growing period of 2013 at the Chonnam National University's research farm (35°10′N, 126°53′E, alt. 33 m) in Gwangju, Chonnam province, South Korea. Chonnam province is one of the major rice growing regions of S. Korea, with a typical East Asian monsoon climate, a mean annual temperature of 13.8 °C and precipitation of between 1391 and 1520 mm/yr (1981–2010). More than 60% of precipitation occurs during the summer monsoon season (July–August). The top soil layer (0–30 cm) is categorized as loam (Sand 388 g kg^{-1}, Silt 378 g kg^{-1}, Clay 234 g kg^{-1}), with a pH 6.5, C_{org} 12.3C g kg^{-1}, available P 13.1 mg P_2O_5 kg^{-1}, CEC 14.4 c mol_c kg^{-1}, and total N before fertilization of 1.0 g N kg^{-1}.

2.2. Experimental design/Description of the experimental plots

An improved rice variety, *Oryza sativa* subsp. Japonica cv. Unkwang (Iksan 435 x Cheolweon 54) was cultivated as flooded paddy crop and as rainfed crop in two adjacent (separated by 100 m) experimental rice fields. Paddy rice was planted in 3 replicate blocks measuring 73.0 m × 19.5 m, with a perimeter cement wall. Sampling was confined to 8 m by 8 m sub-plots at the center of the blocks to minimize edge effects. In the rainfed rice field, we demarcated 3 replicate plots measuring 37.5 m × 28.0 m for our measurements. These plots were randomly selected, but at the middle of the field to avoid edge effects too. In both paddy and rainfed rice, the sample plots were accessed using footbridges to minimize disturbances of the soil and canopy.

2.3. Field management

Measurements were conducted during the 2013 growing season. The rice seedlings were grown for 4 weeks as seedling mats in the greenhouse, before being transplanted into the paddy fields, whereas in rainfed field the rice was directly seeded. Management practices and planting dates, including rice transplanting and harvesting days are summarized in Table 1. Fertilization rate of 115 kg N/ha (80% as basal dosage and 20% during the tillering stage) for paddy and rainfed rice were done before transplanting and at seeding stages, respectively, at a ratio of 11:6:5 (N:P:K), following the recommendations of the Korean Ministry of Agriculture, Food and Rural Affairs (MAFRA). Rice in rainfed and paddy fields were planted at a distance of 10 cm and a line spacing of 30 cm at a seed-density of 50.5 kg/ha. The paddy rice field was kept flooded from 5 days before transplanting until the heading stage (late July).