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Response of Rice Yield in Relation to Solar Radiation and Air Temperature under Soil Water Deficits

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ABSTRACT

The influence of solar radiation and air temperature, in conjunction with soil water deficits occurred at vegetative growth and panicle formation stages, on yield of rice (*Oryza sativa* L. cv. Tainung 67) was studied during the growing seasons of 1991 to 1993. Five levels of water stress treatment, i.e., 0 (control), -0.25, -0.5, -0.75, and -1.0 MPa, were planned by withholding irrigation for each crop. When considering relations of rice production with climatic variables, good agreement was observed between yield and total solar radiation. The rice yield increased with increasing total solar radiation. Similarly, heat summation also had significant effect on rice yield. The yield increased from 5.87 ton ha^{-1} at 2500.4 ℃ season^{-1} in the 2nd crop of 1992 to 7.51 ton ha^{-1} at 2938.9 ℃ season^{-1} in the 1st crop of 1991. On the other hand, no significant difference in rice yield was found among total sunshine hours and rainfall. The rice yield decreased with decreasing soil water potential at all levels of total solar radiation and heat summations. The results indicated that rice yield showed a linear relationship with soil water potential, for example, yield was decreased linearly up to -1.0 MPa for the 1st crop of 1991 and up to -0.75 MPa for the 2nd crop of 1992. Effect of water stress on yield was greater if stress was imposed at the panicle formation stage since significant yield reduction was shown in both crops.

Key words: Rice, Yield, Solar radiation, Heat summation, Water deficits.

土壤缺水時水稻產量與日照及氣溫之關係

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摘　要：本文研究旨在探討不同生育時期土壤缺水對不同期作 (1991-1993) 水稻 (*Oryza sativa* L. cv. Tainung 67) 產量之影響，同時究明水稻產量與日照及積溫間之關係和其在缺水狀況下之變化。田間試驗係在臺灣省農業試驗所農場進行，土壤缺水處理乃以停止灌水方式達成，分為 0(對照) 、-0.25 、-0.5 、-0.75 、及-1.0 MPa 等五種。根據試驗結果，正常灌水狀況之水稻產量與全期日射量呈現正相關，即水稻隨全期日射量增加而增產。水稻產量與全期累積氣溫亦顯示正相關，當全期累積氣溫從 2500.4 ℃ season^{-1}(1992 年二期作) 上升至 2938 ℃ season^{-1}(1991 年一期作) 時，產量自 5.87 ton ha^{-1} 提高為 7.51 ton ha^{-1}。當土壤水分不足時，水稻產量將因土壤缺水程度之增加而減產。在本文試驗期間，水稻產量之降低與水分潛勢呈現直線遞減關係。無論任何期作及年份，土壤缺水發生於穗形成期 (幼穗分化期至抽穗) 之嚴重性均較發生於營養生長期 (分櫱盛期) 為大。

關鍵詞： 水稻，產量，日照量，累積氣溫，缺水。

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INTRODUCTION

The growth and yield of a plant markedly depends on its genetic background as well as on the environmental variables of its habitat (Eskridge and Stevens, 1987; Neild and Richman, 1981; Stevens, 1985; Thompson, 1969a, 1969b). Accordingly, plant adaptation to environment of a particular location can be assessed by observing the stability of yield production to the changes of weather, especially at conditions within the range normally encountered by the plant. Among the climatic factors, solar radiation, air temperature and rainfall play not only a major role on modifying various morphological and physicochemical characters but also determining the plant production (Ballantine and Forde, 1970; Bjorkman and Holmgren, 1963; Louwerse and Zweerde, 1977; Nobel *et al.*, 1975; Gourdon and Planchon, 1982).

Rice is sometimes grown under rainfed cultivation with a limited water source available in Taiwan. Rainfall is erratic and disproportionate while the cost of supplementary irrigation is expensive and restricted. An understanding of yield responses to water deficits at different growth stages and in relation to other climatic factors such as solar radiation and air temperature is therefore needed to optimize water management and cultivation practices.

Various aspects of crop-weather (climate) relationships have been studied to assess the influence of weather on crops (Bair, 1973; Dennett and Diego, 1980; Haun, 1982; Huda *et al.*, 1975; Shanker and Gupta, 1987, 1988; Thompson, 1969a) and to provide useful information in understanding the mechanisms of climate effects. Particularly, Regression models have been developed and tested for predicting irrigated rice yields in relation to major climatic variables during reproductive and ripening stages in 40 environments during 1976-1981 (Seshu and Cady, 1984). As reported that a prediction equation based on radiation and minimum air temperature during the ripening stage of 30 days after flowering demonstrated predictive ability. Models of plant growth responses to solar radiation has also been developed in corn by Linvill *et al.* (1978) and Muchow *et al.* (1990).

In Japan, yield differences associated with solar radiation and air temperature in irrigated rice have been studied. Murata (1975) proposed that radiation is the most important climatic variable in determining rice yield in the middle or southern regions of Japan and temperature is more pronounced in the north. However, Murata (1975) and Yoshida (1983) all emphasized the importance of considering the growth stages of rice when relating growth and yield response to climatic variables.

This study was initiated to investigate yield responses of rice to solar radiation and air temperature and to analyze the changes of its relation under soil water deficits at different growth stages in the varied growing seasons. The approach can be used to explain the adaptibility of rice to particular environments and the capability to drought of different ecological habitats. Such information may also be useful for scheduling irrigations and for modeling rice growth. The objectives were, therefore, aimed to evaluate the importance of solar radiation, air temperature and water supply in rice production. The yielding capacity of rice in relation to solar radiation and air temperature under soil water deficits at different growth stages will also be analyzed.

MATERIALS AND METHODS

Field experiments were conducted at experimental farm of Taiwan Agricultural Research Institute (TARI, 24°02'N, 120° 40'E, elevation of 85 m) during the growing seasons of 1991 to 1993 (Table 1). The soil was a loamy soil, classified as a mixed, nonacid, hyperthermic Fluvaquentic Dystrochrept, with 34.8% sand, 44.7% silt, and 20.5% clay and a pH of 5.05. The soil bulk density was 1.41 g cm^{-3} and soil water contents at field capacity (-0.03 MPa) and wilting point (-1.5 MPa) were 26.21 and 7.17% (by weight), respectively.

Three-leaf old rice (*Oryza sativa* L. cv. Tainung 67) seedlings were transplanted, three plants per hill, in 12 × 12-m plots with 0.30 × 0.15-m row spacings and a population density of 222, 000 hill ha^{-1}. All plots were fertilized with 110 kg N ha^{-1}, 170 kg P ha^{-1} and and 110 kg K ha^{-1} at the time of transplanting as the basal dose. On active tillering, panicle formation and grain-filling stages, additional N (ammonium sulfate) was applied at the rate of 100 kg N ha^{-1} each time. Weed and pest control were practiced as needed. Rice plants were grown in the field under natural climatic conditions. Treatments comprised subjecting plants to soil water stress at vegetative growth stage (active tillering) and panicle formation stage (from panicle initiation to heading), separately, by withholding irrigation. The stressed plants were relieved after the desired levels of water stress were reached. Four soil water potential levels were scheduled, i.e., -0.25, -0.5, -0.75 and -1.0 MPa, though the actual stress levels reached were dependent on weather conditions. The well-irrigated rice was the control. Soil water potential was monitored by gypsum resistance blocks, two for each plot, installed at a depth of 0.20 m. The resistance-water potential relationship was predetermined as that described by Yang *et al.* (1993).

The responses of rice yield to solar radiation and air temperature were evaluated by the total solar radiation (MJ m^{-2} season^{-1}) and heat summation (℃ season^{-1}). The total solar radiation (TSR) is the summation of daily solar radiation for the whole growing season and is computed with the equation

$$TSR = \sum_{i=1}^{n} SRi$$

where SRi is the daily solar radiation (MJ m^{-2} d^{-1}), measured by a radiometer (MS-61, Eko Instr. Co., Japan), and n is the days from transplanting to harvest. The equation used to calculate heat summation (HS) is defined as

$$HS = \sum_{j=1}^{n} Tj$$

where Tj is the daily average of hourly air temperature, measured by temperature/relative humidity probes (Model E-701, Nakaasa Instr. Co., LTD, Japan), beginning from transplanting (T1) to harvest (Tn). The daily average of hourly air temperature is calculated in ℃ using the following equation

$$T = (\sum_{k=1}^{24} Tk)/24$$

in which Tk is the hourly average of air temperature. The changes of these relationships under soil water deficits occurring at different growth phases were studied using regression analysis. Additionally, the effects of total sunshine hours (hr season^{-1}), measured by radiation meter (model H-061, Yokogawa Weather Co., Japan), and total rainfall (mm season^{-1}), measured by rain gauge (Model B-011, Nakaasa Instr. Co., LTD, Japan), on rice yield were also examined.

The experiment was planned as a split-plot design with three or four replications. Main treatments were the growth stages of rice and the subtreatments were the varied levels of water stress. Standard deviation and regression analysis were employed for assessment. Yield (brown rice) was determined at harvest from an area of 10.5 m^2.

RESULTS

Yields of well-irrigated rice from the growing seasons of 1991 to 1993 were randomly distributed as shown in Figure 1. However, good agreement is observed between yield and total solar radiation (Fig. 2). The yield of rice in-

Table 1. Growth duration and schedule of water stress treatments at different growth phases during the crop seasons of 1991 to 1993.

Crop season	Growth stage	Stress period	Growth duration
1991			
1st crop	vegetative	4/ 8 – 4/29	2/26 – 6/27
	panicle formation	5/ 3 – 6/ 7	
2nd crop	vegetative	8/19 – 9/ 4	7/31 – 11/11
	panicle formation	9/10 – 9/29	
1992			
1st crop	vegetative	4/25 – 5/ 6	2/21 – 6/29
2nd crop	vegetative	9/ 8 – 9/20	7/28 – 11/2
	panicle formation	9/25 – 10/15	
1993			
1st crop	vegetative	4/10 – 4/24	2/17 – 6/18
	panicle formation	5/6 – 5/24	

creased with increasing total solar radiation during the growing seasons of 1991 to 1993. Heat summation also had significant effect on rice yield (Fig. 3). Yield increased from 5.87 ton ha^{-1} at 2500.4 ℃ $season^{-1}$ in the 2nd crop of 1992 to 7.51 ton ha^{-1} at 2938.9 ℃ $season^{-1}$ in the 1st crop of 1991.

The yield of rice decreased with decreasing soil water potential at all levels of total solar radiation and heat summation considered (Figs. 4 and 5). At same level of total solar radiation (Fig. 4) and heat summation (Fig. 5), rice yield was lowered by soil water deficits. A parallel fashion was observed in these relationships, yet the rate of yield decrease was more rapidly when water stress occurred in the panicle formation stage than in the vegetative growth stage (Figs. 4 and 5). On the other hand, total sunshine hours and rainfall had no significant effect on rice yield (Fig. 6).

As the experiments were conducted in the field, the actual stress levels reached were dependent on weather conditions. Nevertheless, yield-soil water potential relationship was observed in 1991-1993 growing seasons. In the 1st crop of 1991, yield of rice cultivar Tainung 67 showed a linear relationship with soil water potential up to -1.0 MPa and up to -0.75 MPa for the 2nd crop of 1992 (Fig. 7). Water stress treatments increased the percentage of yield reduction of rice, especially when stress occurred at the panicle formation stage. Rice experienced stress of -1.0 MPa of soil water potential at panicle formation stage in the 1st crop of 1991 had substantially yield reduction up to 70%. Rice yields increased by 23 and 42% in the 1st crop of 1991, and by 21 and 37 % in the 2nd crop of 1992, when soil water potential increased from -0.75 MPa to saturated condition at vegetative growth and panicle formation stages, respectively.

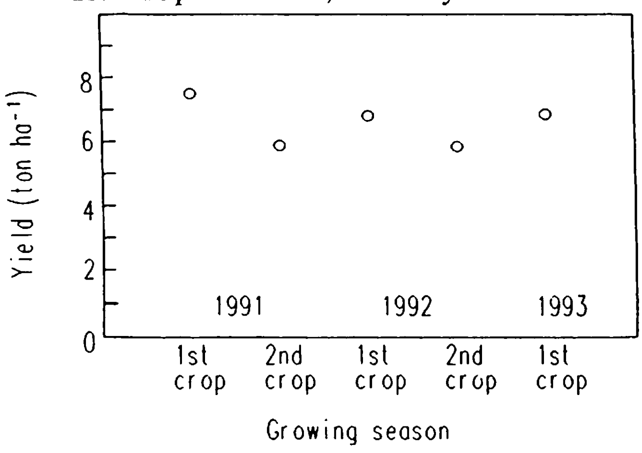

Fig. 1. Yields of rice cultivar Tainung 67 from different growing seasons of 1991 to 1993.

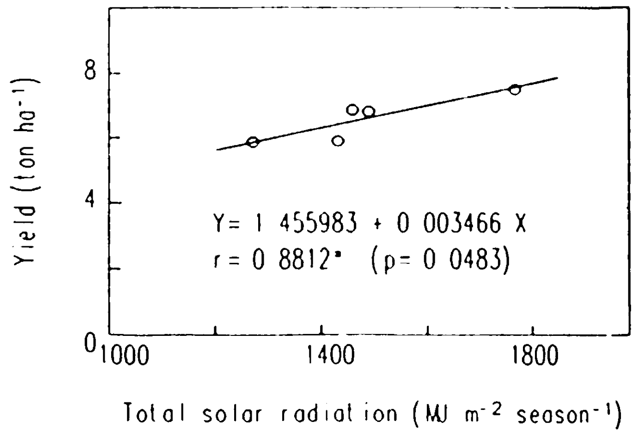

Fig. 2. Relationship between yield and total solar radiation of rice cultivar Tainung 67 in well-irrigated condition.

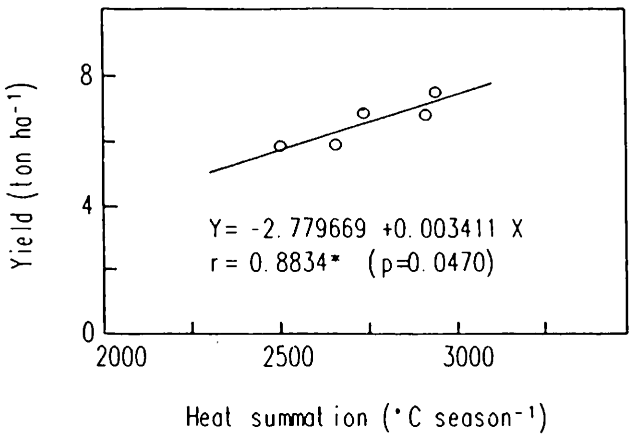

Fig. 3. Relationship between yield and heat summation of rice cultivar Tainung 67 in well-irrigated condition.

DISCUSSION

The results of rice yield increased with increasing total solar radiation and heat summation reasonably correspond to known physiological concepts. As found in other species (Peet *et al.*, 1977), the CO_2 exchange rate, transpiration rate, stomatal conductance and chlorophyll content were increased with increasing temperature under light saturated condition. Low light intensity reduced dry matter accumulation of both the stem and ear and resulted in a reduction in the final number of endosperm cells formed in the grain

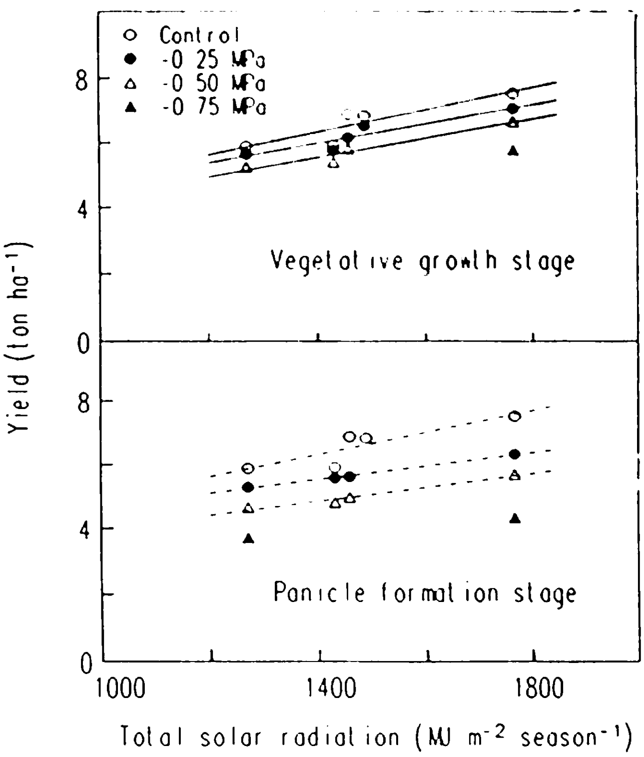

Fig. 4. Relationship between yield and total solar radiation of rice cultivar Tainung 67 under soil water deficits at different growth stages.

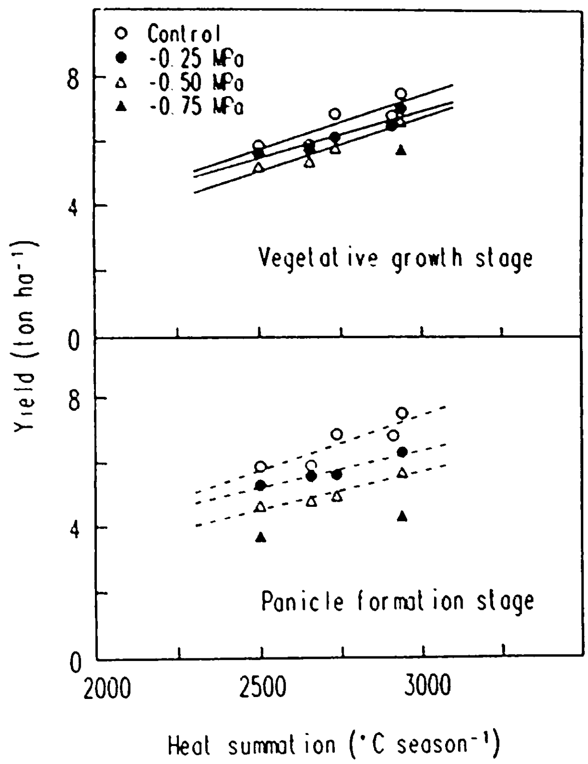

Fig. 5. Relationship between yield and heat summation of rice cultivar Tainung 67 under soil water deficits at different growth stages.

Wardlaw, 1970). Higher temperature resulted in a greater rate of cell division in the endosperm tissue and mesophyll and a shortening of the stem growth period with a corresponding increase of grain (Wardlaw, 1970), especially for species originating from tropical areas where the optimal temperature for photosynthesis and growth is between 30 to 35 ℃ (Cooper and Tainton, 1968; Duan and Hesketh, 1968). Since yield is the product of rate and duration of dry matter production and accumulation over the growing season, it is no surprise that the increase of total solar radiation and heat summation stimulated rice yield.

When the soil dries, the resistance of water flow from the soil to the plant roots will increase (Taylor and Gardner, 1963). Ultimately, the continous loss of water through leaves and other tissues will surpass water absorption from soil and would result in turgor reduction and hence reduces leaf enlargement, cambial growth, stomatal opening and associated carbon assimilation (Boyer, 1968, 1976; Cowan, and Farquhar, 1977; Hsiao, 1973). On a daily basis drought-induced stomatal closure may optimize the water use efficiency (Cowan and Farquhar, 1977), but may shut down stomata, reduced transpiration and impaired photosynthetic ability limiting dry matter production and accumulation and therefore restrict yield if drought prolonged. As that indicated by the results, yield of rice decreased as soil water potential decreased at all levels of total solar radiation and heat summations. Water deficit even resulted in a more serious effect when occurred in the panicle formation stage than in the vegetative growth stage.

The physiological aspects of plant metabolism affected by water stress have been well established. Biswas and Choudhuri (1984) found that the contents of chlorophyll, protein, RNA and the activity of catalase were lowered by water stress, while free proline accumulation and activities of protease, RNase and peroxidase were increased. They further stated that water stress at the reproductive stage induced similar changes as in the vegetative stage, but the removal of stress could not recover to the same extent as that at the vegetative stage. Particularly, water stress at heading stage adversely affected grain

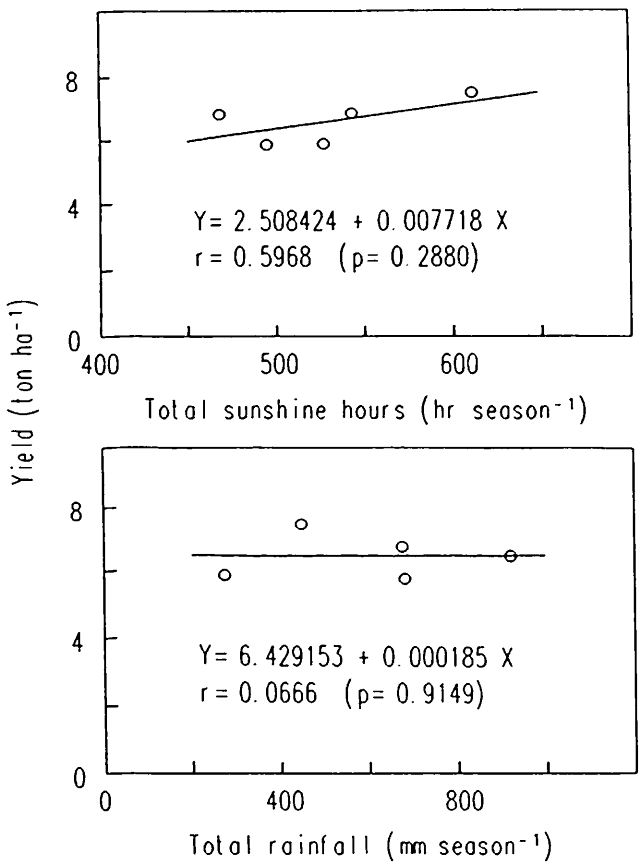

Fig. 6. Relationships between yield and total sunshine hours and total rainfall of rice cultivar Tainung 67.

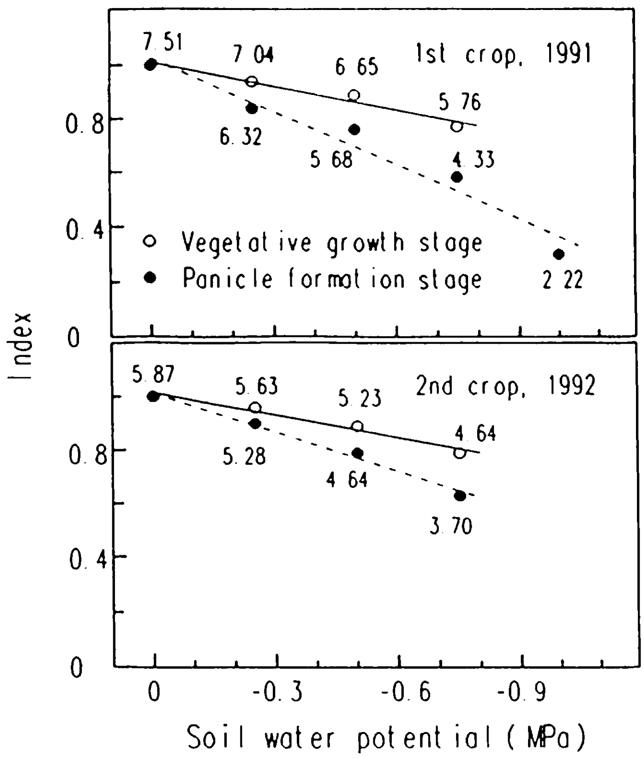

Fig. 7. Effects of soil water deficits on yield of rice cultivar Tainung 67 at the 1st crop of 1991 and the 2nd crop of 1992. The values of yield harvested from water stress treatments at different growth phases are listed. The index value was calculated by dividing yield from treated rice with yield from the control at the same crop.

formation and at milk-ripe stage affected grain mass. Kobata and Takami (1981) showed that yield of rice experienced drought during the early stage of grain-filling yielded less than that of well-watered rice. The lack of assimilate supply to vegetative tissues and the grain may be resposible for reduced grain yield under prolonged stress (Kobata and Takami, 1983). Similar results were reported in maize (Jurgens *et al.*, 1978; Yang *et al.*, 1993), wheat (Wardlaw, 1971) and soybean (Pahalwan and Tripathi, 1984). Water stress can also affect peanut and corn yields differentially depending on time of occurrence and intensity (Nageswara Rao *et al.*, 1985, 1988; Yang *et al.*, 1993).

Moreover, the results indicated that the rice yield showed a linear relationship with soil water potential in both the 1st and the 2nd crops. The yield increased linearly when soil water potential increased from -1.0 MPa. Drought effect on yield was relatively greater if water stress imposed at the panicle formation stage. As explained in paragraph above, a more decline pattern of yield reduction was shown in either crop in this study. The results also revealed that yield was not significantly different in vegetative-stressed treatments up to -0.25 MPa but was significantly reduced in panicle formation phase at the same strss level (data not shown). Therefore, when planning irrigation schedule with limited water source, it would be a better strategy to place weighted amount of water in the reproductive growth for better yield.

This study shows the advantages of utilizing total solar radiation and/or heat summation on explaining the changes of rice yield and in assessing the variations of these relationships when water stress imposed at different growth stages in the varied growing seasons. However, the extended interpretation of the present results must be careful due to limited data, i.e., the number of years and locations are scantly. A more thorough research considertemporal and distributional variabilities of yield-climate relations should be conducted for simulation of rice yield from climatic variables.

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