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Increasing the Yield Plateau in Rice and the Role of Global Climate Change

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Abstract

To cope with estimated population growth in Asia, attainable rice yield potential must increase in the irrigated lowlands. At odds with this goal is the fact that yield potential of released high yielding rice varieties has remained constant since the release of IR8 in the late 1960s, although yield per day increased as a result of shorter growth duration and host plant resistance was improved. For example, highest rice yields of IR72 (released in 1987) were 6 and 9.5 t ha^{-1}, in the 1991 wet season and the 1992 dry season, respectively, in a tropical environment with good agronomic management. These yields are comparable but no higher, than the highest yields attained by IR8 in the same environment more than 20 years ago. Detailed growth analysis from these recent studies allowed us to improve an eco-physiological model for rice growth. Subsequent simulations demonstrated accurate prediction of wet and dry season rice yield. The model was then used to evaluate the effects of global climate change as expected by the year 2020. Changes in temperature and atmospheric CO_2 had relatively small effects on simulated rice growth and yield compared with (1) the impact of crop management practices in high-yielding environments and (2) genetic improvement that could further increase yield potential. Varieties with a longer grain filling duration will be needed to increase the yield plateau and to reverse negative effects of increased temperature.

Keywords: climate change, simulation model, rice yield potential

1. Introduction

At present, global rice supplies depend heavily on rice produced in irrigated rice eco-systems. Rice production must increase by 65% from 1992 to the year 2020 to keep up with estimated population growth rates (IRRI, 1989). The extra rice production must come from increased production per unit area. Fortunately, yields are still increasing in most irrigated areas, presumably as a result of improved crop and soil management and improved varieties. In Northeast and East Asia, however, yields will quickly reach the plateau level, which is determined by the yield potential of current varieties (Penning de Vries, 1992). Thus, new varieties with a higher yield potential will be needed early in the next century.

Long term experiments have demonstrated problems in sustaining high yields in intensive rice systems (Flinn *et al.*, 1982). On IRRI's experimental farm intensively managed rice (IR8) yielded 9 - 10 t ha^{-1} in the late 1960s, but rice yields generally did not exceed 6 - 7 t ha^{-1} in the past decade. In this paper, we will present some results of experiments that were conducted to quantify the yield potential of current varieties and to identify the agronomic practices required to express the existing potential. A simulation model for potential growth and production of rice was evaluated using these data and further used to explore possibilities to increase the rice yield potential and to quantify the impact of global climate change on rice production in the tropics.

2. Yield potential in rice

The yield potential of a crop is only determined by varietal characteristics and the seasonal pattern of environmental variables such as temperature and radiation. Thus, crop yield potential differs among environments, in different years and in seasons in the same year. Maximum rice yields of 10 t ha^{-1} have been achieved in tropical environments, and yields of 13 t ha^{-1} are possible in more temperate environments like Japan and China (Yoshida, 1981). Unfortunately, detailed data sets that can be used to obtain a quantitative understanding of the determinants of rice yield potential are rare. Simulation models that were calibrated using the available data sets, simulate maximum potential yields of only 8 t ha^{-1} for Los Banos weather conditions (Herrera-Reyes and Penning de Vries, 1989; Penning de Vries, 1991, 1992). This simulated yield suggests that yield potential of current varieties is now lower than that of IR8, which yielded 9 - 10 t ha^{-1} in the late 1960s. It was hypothesized that the current low yields at IRRI's farm were partly related to a change in the N supply environment causing low N concentrations in leaf tissue, especially during the grain filling period, resulting in early senescence of leaves and low rates of photosynthesis (Kropff *et al.*, 1992; Cassman *et al.*, 1992). Field experiments were conducted to quantify the yield potential and determinants of yield potential with improved agronomic management.

In the 1991 wet season (WS) and in the 1992 dry season (DS) IR72 and a new elite line IR58109-113-3-3-2 were grown at IRRI's farm under irrigated conditions. Nitrogen inputs were 110 kg N ha^{-1} (WS) and 225 kg N ha^{-1} (DS). These rates were 30 kg N ha^{-1} (WS) and 105 kg N ha^{-1} (DS) higher than the current practice at IRRI, and included a late application at flowering to maintain leaf N status during grain filling. Dry weights of organs and N concentration of tissue were measured periodically. The eco-physiological growth model described by Kropff and Spitters (1992) was evaluated with the data from both seasons.

Total dry matter production and grain yield differed markedly in the WS and DS for both varieties (Table 1). Yields were comparable to yields reported in the late 1960s for IR8 (Yoshida, 1981): about 6 t ha^{-1} in the WS and 9 - 10 t ha^{-1} in the DS, indicating that the genetic potential remained the same, despite differences in growth duration (IR72 has a growth duration of about 110 days *versus* 125 days for IR8). The yield difference between the seasons can be partly explained by differences in radiation levels and temperature: mean daily global radiation was 14 MJ m^{-2} d^{-1} in the WS and 18 MJ m^{-2} d^{-1} in the DS, and daily mean temperature was 27 °C in the WS and 26 °C in the DS. After the 1991 wet season experiments, the model was developed and parameterized and used to predict yields and N requirements for a dry season. Using the varietal parameters derived from the 1991 wet season experiments (like development rates, dry matter distribution patterns and leaf N concentrations), the model predicted yields of about 8 t ha^{-1} with typical DS weather data (Kropff *et al.*, 1992). If the leaf N concentration measured in the dry season was input to the model, yields of about 9.5 t ha^{-1} were simulated with the DS weather data. Leaf N concentrations were about 1.4 times higher in the DS. These results demonstrate that differences in weather and crop N status determined yield differences between WS and DS. The need for changes in N management practices to sustain high yields in intensive rice systems

Table 1. Observed and simulated grain yields (panicle dry weight) for the 1991 wet season and the 1992 dry season with IR72 and a new line elite IR58109-113-3-3-2.

	1991 Wet Season		1992 Dry Season	
	Observed ($kg\ ha^{-1}$)	Simulated ($kg\ ha^{-1}$)	Observed ($kg\ ha^{-1}$)	Simulated ($kg\ ha^{-1}$)
IR72	5674±229	5981	9558±288	9372
IR58109-113-3-3-2	6111±182	6034	9709±242	10024

was also demonstrated in a long term intensive rice cropping experiment at IRRI's experimental farm. In the late 1960s and early 1970s, when intensive rice cropping just started at IRRI's experimental farm, 100 kg N ha^{-1} was sufficient to obtain yields of about 9 t ha^{-1}, whereas 190 kg N ha^{-1} was needed to obtain these yield levels in 1992. This leads to the conclusion that the increased amount of N fertilizer, needed to obtain these high yields, has to be the result of a reduced soil N supply, because N recovery rates are similar (Cassman *et al.*, 1992, Kropff *et al.*, 1992).

3. Increasing the yield plateau in rice and the impact of global climate change.

The physiological characteristics needed to develop new rice varieties with an increased yield potential have been determined using models in several studies (Penning de Vries, 1991; Dingkuhn *et al.*, 1991; Kropff *et al.*, 1992). Because large changes in photosynthetic efficiency and respiration costs are not to be expected, increased yield potential must come from increased allocation of stem reserves, from a prolonged grain filling period, from an increased growth rate during grain filling or from a combination of these sources. Penning de Vries (1991), Dingkuhn *et al.* (1991) and Kropff *et al.* (1992) emphasized the lengthening of grain filling duration as the main option to increase the yield plateau. To achieve 15 t ha^{-1}, 38 days of effective grain filling would be needed. The yield potential of a rice variety at higher latitudes is greater than in the tropics for the same reason. The grain filling period is extended as a result of lower average temperature. The eco-physiological model indeed predicts an increase in rice yield potential for Los Banos of 2 t ha^{-1} with a reduction of mean temperature by 3 °C.

A temperature increase of 1 °C and a CO_2 rise of 50 ppm can be expected based on predictions made by Global Circulation Models for the year 2020. The effects of these climate changes were quantified by the simulation model. In the model, temperature affects the rate of photosynthesis, the respiration rate and the rate of phenological development. CO_2 only affects the rate of photosynthesis. The model predicted a yield reduction of 8 - 9% for both varieties in both the DS and the WS as a result of a temperature increase of 1 °C. Increased CO_2 partly reversed this effect resulting in yield reductions of only 3%. A 5% reduction in radiation level resulted in a yield reduction of about 3%. Penning de Vries (1992) simulated yield effects of increased temperatures, assuming that temperature does not affect growth duration. That was based on the assumption that farmers will select varieties with a longer grain filling duration to compensate for these effects. In preliminary experiments, however, we found large genetic variation in the length of the grain filling period when expressed on a single panicle basis, but not on a whole crop basis. Research on this aspect of grain filling duration will have to be intensified.

4. Conclusion

The results of this study indicate that potential yield in the most recent rice varieties is similar to that of the original modern high yielding varieties under tropical conditions, and this despite the longer growth duration of IR8. The simulation model accurately simulated differences between DS and WS yields on the basis of measured temperature and radiation data, and measured N content of the leaf canopy. With regard to climate change, the model predicts that rice yields will be more sensitive to temperature increase than to increased CO_2 levels in the tropics. Model analyses showed that varieties with a longer grain filling duration will be needed to increase the yield plateau and to reverse negative effects of increased temperature.

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