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Varietal improvement options for higher rice productivity in salt affected areas using crop modelling

Ando M. Radanielson[a,*], Donald S. Gaydon[b,c], Md. Mahbubur Rahman Khan[d], Apurbo K. Chaki[c,d], Md. Atikur Rahman[d], Olivyn Angeles[a], Tao Li[a], A. Ismail[a,*]

[a] International Rice Research Institute, Philippines
[b] CSIRO Agriculture and Food, Brisbane, Australia
[c] School of Agriculture and Food Sciences, The University of Queensland, St Lucia, Brisbane, Australia
[d] On-Farm Research Division, Bangladesh Agricultural Research Institute (BARI), Joydebpur, Gazipur 1701, Bangladesh

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ABSTRACT

The rice model ORYZA v3 has been recently improved to account for salt stress effect on rice crop growth and yield. This paper details subsequent studies using the improved model to explore opportunities for improving salinity tolerance in rice. The objective was to identify combinations of plant traits influencing rice responses to salinity and to quantify yield gains by improving these traits. The ORYZA v3 model was calibrated and validated with field experimental data collected between 2012 and 2014 in Satkhira, Bangladesh and Infanta, Quezon, Philippines, then used for simulations scenario considering virtual varieties possessing different combinations of crop model parameter values related to crop salinity response and the soil salinity dynamic observed at Satkhira site. Simulation results showed that (i) short duration varieties could escape end of season increase in salinity, while long duration varieties could benefit from an irrigated desalinization period occurring during the later stages of crop growth in the Satkhira situation; (ii) combining short duration growth with salt tolerance (bTR and bPN) above 12 $dS\,m^{-1}$ and a resilience trait (aSalt) of 0.11 in a variety, allows maintenance of 65–70% of rice yield under increasing salinity levels of up to 16 $dS\,m^{-1}$; and (iii) increasing the value of the tolerance parameter b by 1% results in 0.3–0.4% increase in yield. These results are relevant for defining directions to increase rice productivity in saline environments, based on improvements in phenology and quantifiable salt tolerance traits.

1. Introduction

The coastal zones of Bangladesh are among the world's most vulnerable areas to climate change. Sea level rise and reduced freshwater flow from upper catchments are the main factors leading to increasing soil and water salinity with negative effects on crop production (Dasgupta et al., 2014). More than 53% of the country's cultivated area is exposed to salinity, with rice as the main crop (Haque, 2006; Dasgupta et al., 2009). Improving rice cropping system productivity in salt affected areas is therefore a major challenge in developing the resilience of crop production in a changing climate and maintaining the country food security.

Soil salinity dynamics are among the main biophysical factors determining timing in the rice cropping calendar for this salt-affected environment (Gaydon et al., 2014, 2018). Cropping in the wet season starts after sufficient freshwater has desalinized the upper soil layers to ensure that wet-season rice (Aman) is not affected by salinity. During the dry season, the availability of freshwater for irrigation becomes limited as the salinity of surrounding rivers water increases. The potential for producing a second rice crop in the dry 'boro' season currently depends on the availability of freshwater stored from the wet season. Adaptation strategies allowing rice cropping in the dry season require then setting appropriate sowing dates, together with the use of improved salt-tolerant rice varieties and freshwater management (Ismail et al., 2007; Deryng et al., 2011; Gaydon et al., 2018).

The date of sowing plays a crucial role in optimising crop production and in climate change adaptation (Deryng et al., 2011; Gaydon et al., 2014, 2018; Radanielson et al., 2015). In wheat, a loss of 57 kg ha^{-1} of yield per day has been reported with delay in sowing beyond 20th November (Krupnik et al., 2015). For wet season rice, sowing around the 30th of May has been reported to lead to maximum yield (Ahmed et al., 2014). In the dry season, Mondal et al. (2010, 2015)

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* Corresponding authors.

E-mail addresses: a.radanielson@irri.org (A.M. Radanielson), don.gaydon@csiro.au (D.S. Gaydon), mahbubur.bio@bari.gov.bd (Md. M. Rahman Khan), a.chaki@uq.edu.au (A.K. Chaki), atiksoil@bari.gov.bd (Md. A. Rahman), o.angeles@irri.org (O. Angeles), t.li@irri.org (T. Li), a.ismail@irri.org (A. Ismail).

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found that sowing around the 15th of November is optimum for 'boro' rice in Bangladesh. This has been supported by some recent modelling studies (Gaydon et al., 2018). The determination of the optimum cropping calendar therefore, changes with the crop, the variety and the climatic conditions. This kind of time and site-specific management is more complex when considering the complexity of salinity dynamics over time and space in the field.

Rice is one of few crops that can be successfully grown in salt-affected soils, even though it is considered sensitive to salinity. This is because growing in flooded fields allows partial desalinization of the soil and reduces the impact of salinity on crop growth and yield (Ismail et al., 2007; Singh et al., 2010). Significant efforts have been devoted to breed salt tolerant rice varieties in the recent past, and several varieties were developed through combining conventional and molecular breeding (Gregorio et al., 2002; Islam et al., 2008; Kole et al., 2015). Progress in understanding physiological mechanisms and genetic control of salinity tolerance has accelerated and enhanced the breeding of tolerant varieties (Ismail et al., 2007; Thomson et al., 2010). However with the anticipated worsening conditions of salinity caused by climate change, especially in coastal tropics, it is expected that further improvement in salinity tolerance is required in future varieties (Nicholls et al., 2016; Clarke et al., 2015; IPCC, 2014). To sustain rice production in the coastal saline areas, varieties combining tolerance to multiple stresses such as salinity, drought and submergence are required (Ismail et al., 2007, 2009; Wassmann et al., 2009a; Kole et al., 2015). The development of such 'climate ready' varieties remains challenging and requires a multidisciplinary approach, particularly when considering the stability of these varieties across environments (Islam et al., 2015). Conventional varietal assessment using multi environment trials is limited in its ability to explore different combinations of environmental factors and crop traits. In addition, time and site-specific management of these trials are costly and time consuming. Temporal and spatial variability of salinity adds further complexity to such varietal assessment.

Simulation modelling provides a practical means for addressing this complexity. It offers an alternative to examine possible combinations of crop traits and to assess their performance in real environments, therefore accelerating selection and delivery in breeding. Process-based crop models use quantitative descriptions of various factors limiting crop productivity. By detangling crop productivity into key factors, a platform for virtual experiments is created to test hypotheses and quantify impacts of variation in environments, management and genotype on grain yield, besides other system variables like water productivity (Balwinder-Singh et al., 2015; Radanielson et al., 2015; Gaydon et al., 2018).

Crop modelling allows extrapolation of field experiment results to long-term understanding via multi-year simulation. Consideration of system performance in both historical and future conditions is possible using daily measured and generated climate data, respectively. This provides a greater insight into long-term system risk and variability than could possibly be obtained from several years of experimental results alone. Models can effectively be used to determine optimal management practices and can integrate variability in crop genotypic responses (Matthews et al., 1997; Bouman and van Laar, 2006; Bannayan et al., 2005; Li et al., 2013; Balwinder-Singh et al., 2015). Applications of models for crop improvement include evaluating the impact of specific characteristics on yield (and its season-to-season variability) and the determination of optimum ideotypes for particular production ecosystems (Sinclair and Muchow, 2001; Chapman, 2008; Chenu et al., 2008; Casadebaig et al., 2011). Characterizing target population environments is also among the most frequent uses of modelling for variety assessment (Chenu et al., 2009a). Modelling assists decision- making in breeding programs and can enhance the rate of yield gain within groups of environments (Hammer et al., 2005; Chenu et al., 2011). Studies have also demonstrated the usefulness of modelling by integrating advances in crop physiology to enhance breeding programs, particularly in improving complex traits such yield and drought tolerance (Hammer et al., 2002; Cooper et al., 2005; Chenu et al., 2009b). However, these approaches have not been sufficiently employed in rice breeding programs. The crop model ORYZA v3 (Bouman et al., 2001; Li et al., 2017) has been recently used to assess drought-tolerant traits in rainfed rice systems in South Asia (Li et al., 2013). It has also been applied to estimate climate change effects on rainfed rice systems and demonstrate the importance of modifying sowing dates to cope with climate change (Li et al., 2015).

In this study, we demonstrate the use of crop modelling to quantify the contribution of salinity tolerance and resilience traits on rice yield variability for areas with light to moderate salt stress such the Satkhira region of Bangladesh (8–12 dS m^{-1}). As part of the study, we characterized the salt tolerant variety BRRI dhan47. The main objective was to define approaches and options for further improvement of this variety as well as future varieties for the region, using modelling. In salt-affected areas such as coastal Bangladesh, variability of soil salinity is driven by the interaction of climatic and environmental factors (rainfall, temperature, river salinity), with crop management (irrigation and sowing dates). Suitable varieties must exhibit specific traits to cope with these environmental and management conditions. The rice crop model ORYZA v3 (Li et al., 2017) used in this study has been recently improved to represent the effects of salinity on rice growth and yield (Radanielson et al., 2018a). We initially conducted field experiments to calibrate and validate the model's performance in simulating genotypic variability in rice response to salinity. Scenario analyses were then performed using long-term historical climate data for Satkhira, Bangladesh, investigating the effect of early and late sowing dates with a range of virtual salinity trait combinations in a rice genotype.

2. Materials and methods

The initial aim of this research was to parameterise, calibrate and validate the ORYZA v3 model (Radanielson et al., 2018a; Li et al., 2017) using data from several years of field trials in different environments (Philippines and Bangladesh), with a range of existing rice varieties contrasting in their salinity tolerance. Successful model performance in this process facilitated subsequent scenario analyses, investigating performance of virtual varieties for the coastal Bangladesh environment.

2.1. Model calibration and validation

2.1.1. Field experiments

2.1.1.1. Rice genotypes. Four field experiments were conducted using three varieties of contrasting salinity tolerance: BRRI dhan47, IR64 and IR29. BRRI dhan47 is one of the salt tolerant varieties used by farmers in Bangladesh (Islam et al., 2008). The variety IR29 is generally used by breeders as a sensitive check in breeding for salinity tolerance; and IR64 is a widely known variety, frequently used as high yielding parent in breeding with intermediate salt tolerance.

2.1.1.2. Field experimental design. The experiments were performed during the dry seasons of 2012–2014 and were conducted at two sites. Experiments (Expts) 1 and 2 were conducted at Infanta, Quezon Philippines (14° 45′N, 121°41′E) using the three varieties. Expts 3 and 4 were conducted at Satkhira, Bangladesh (24° 12′N', 90°12′E) using BRRI dhan47 (Table 1). Expts 1 and 2 were established in a randomized split-plot design with three replicates. Each experiment had four treatments of irrigation management (main factor) and three varieties (subfactors). Expts 3 and 4 had three and four irrigation management treatments, respectively, in a randomized block design with three replicates. The irrigation treatments were managed to create salt stress conditions in the field covering 4 salinity levels, corresponding to average soil salinities of 0–2 dS m^{-1}, 2–4 dS m^{-1}, 6–8 dS m^{-1} and higher than 10 dS m^{-1} (Table 1).