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Simulating rice and maize yield potential in the humid tropical environment of Indonesia

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ABSTRACT

Little is known about the yield potential of modern rice and, particularly, maize cultivars in the tropical humid environment of Indonesia where farmers can grow 2–3 consecutive crops on the same piece of land per year. This study provides a first step to fill this knowledge gap by using two crop simulation models to estimate yield potential for rice and maize based on experiments conducted across multiple site-years and measured weather and soil data. Data collected from well-managed irrigated experiments, with observed yields ranging from 7.8 to 10 Mg ha^{-1} (rice) and 12 to 14.4 Mg ha^{-1} (maize), were used to calibrate phenology and growth coefficients for both a rice (OryzaV3) and maize crop model (Hybrid Maize). The calibration was performed for commercial, high-yielding irrigated rice and maize cultivars. Subsequently, calibrated models were evaluated on their ability to simulate yield potential using an independent database available from variety (irrigated rice) and fertilizer (irrigated and rainfed maize) trials conducted at multiple site-years across major rice and maize producing areas in Indonesia. Calibrated coefficients for rice were robust at reproducing observed leaf area, aboveground biomass, and biomass partitioning to different plant organs. In the case of maize, close agreement between simulated and observed yields suggests that the generic growth model coefficients originally derived for temperate maize performed well at simulating yield potential of modern tropical maize hybrids. The two models reproduced with acceptable performance the maximum observed yields across variety and fertilizer trials, except for rainfed maize grown in a region with very heavy clay soils. Across site-years, yield potential for irrigated rice and maize averaged 9.1 and 11.6 Mg ha^{-1}, respectively, while rainfed maize averaged 11.5 Mg ha^{-1}. Comparison between simulated yields and average national rice and maize yields (5.2 and 5 Mg ha^{-1}, respectively) suggested that room exists to further increase average farmer yields in rice and maize-based crop systems. Our study also highlighted the high yield potential of modern maize hybrids grown in intensive crop sequences in the humid tropics (> 10 Mg ha^{-1}). The two models evaluated here can be used to benchmark productivity in rice and maize crop systems in the humid tropical environments of South East Asia and fine tune current management practices and inputs application.

1. Introduction

Yield potential (Yp) is defined as the yield of a well-adapted crop cultivar with non-limiting water and nutrients, and with biotic stresses effectively controlled (Evans, 1993). Water-limited yield potential (Yw) is similar to Yp but it also accounts for the influence of water supply amount and distribution during the growing season and soil properties influencing the crop water balance, such as rootable soil depth, available-water holding capacity, and terrain slope (Cassman et al., 2003; van Ittersum et al., 2013). Robust estimates of Yp and Yw are needed to assess potential extra food production, set realistic yield goals and associated water and nutrient requirements, and identify opportunities for improving yield and input-use efficiency. Crop simulation models provide a robust approach for estimating Yp and Yw (van Ittersum et al., 2013). These models rely on weather, soil, and management data to simulate the influence of genotype, environment, and

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management practices on crop growth, development, and yield (Grassini et al., 2015; Rotter et al., 2015).

Multiple rice and/or maize crops are often grown on the same piece of land within a 12-month period in the humid tropical environment of South East Asia (Pasuquin et al., 2014). For example, up to three crops per year can be grown in irrigated and favorable rainfed environments of Indonesia. Due to a combination of high cropping intensity and large arable land, Indonesia is the third and fifth largest rice and maize producing country in the globe, respectively (FAOSTAT, 2017). Still, Indonesia has imported substantial amounts of maize and rice grain during recent decades. At the same time, there has been massive cropland conversion for industrial and residential uses (d'Amour et al., 2017). Hence, it is crucial for Indonesia, as well as other countries in South East Asia, to understand what the extra crop production potential is on existing cropland and identify those factors that constrain on-farm yields. Few studies have attempted to estimate rice and, in particular, maize Yp and Yw in Indonesia using crop simulation models (Boling et al., 2004, 2007, 2008; Timsina et al., 2011; Laborte et al., 2012; Pasuquin et al., 2014; Stuart et al., 2016). These previous attempts suffered from limitations and/or sources of uncertainty. First, most of these studies have focused at estimating Yp (or Yw) using models that were calibrated for individual site-years; hence, it is unknown how robust these models are at estimating Yp (or Yw) across Indonesia's wide range of environments and cropping systems. Second, previous studies have relied on coarse-scale gridded and/or generated weather data, which can lead to important biases in simulated Yp and Yw (van Wart et al., 2013, 2015). Finally, many of these studies have used generic model coefficients derived from outdated cultivars that are not representative of modern high-yielding cultivars and/or from experiments that did not reach near-optimal conditions for crop growth, which may have led to an underestimation of Yp (or Yw). For example, Boling et al. (2004, 2007, 2008) reported Yp of *ca.* 4.5 Mg ha^{-1} for irrigated rice in Central Java. We note that this estimate of Yp is lower than current average farmer yield in the same region (*ca.* 5 Mg ha^{-1}) and the Yp of *ca.* 9-10 Mg ha^{-1} expected for irrigated rice in South East Asia (Kropff et al., 1996; Peng et al., 1999).

Robust calibration and evaluation of crop models requires experimental data from crops grown under near-optimal conditions that allow expression of Yp (irrigated) and Yw (rainfed crops), including crop variables (yield, phenology, *etc.*) and weather, soil, and management data needed to simulate site-year specific conditions. However, it is difficult to ensure near-optimal growing conditions, even in controlled experimental plots, due to the multitude of factors influencing crop growth and the difficulties in removing every single limiting factor across space and time (Cassman et al., 2003). These limiting factors include (i) incidence of insect pests and pathogens, which are especially problematic in the humid tropics, (ii) insufficient supply of water (in the case of irrigated crops) and plant nutrients, and (iii) sub-optimal management in relation with transplanting, sowing date, plant density, *etc.* (Lu et al., 2007; Laborte et al., 2012; GRiSP, 2013; Buresh et al., 2015; Castex et al., 2018; Stuart et al., 2016). Likewise, it is difficult to access high-quality measured weather and soil data in many regions of the world, which is needed to conduct site-specific simulations of Yp and Yw (Grassini et al., 2015). Due to lack of data, many studies have relied on coarse-scale or poor quality weather and soil data for model calibration and evaluation, which, as mentioned previously, can seriously distort resulting Yp and Yw estimates (Van Wart et al., 2013, 2015). We are not aware of any explicit effort to calibrate and evaluate crop models for modern high-yielding rice and maize cultivars in Indonesia using data collected from well-managed experiments coupled with high-quality on-site weather and soil data.

The present study made a first step towards a better estimation of Yp and Yw in intensive rice- and maize-based cropping systems in tropical humid environments using high-quality experimental data from modern high-yield cultivars and measured weather data and soil properties. Our objective was to calibrate two crop models (ORYZA and Hybrid Maize) for modern rice and maize cultivars and to evaluate the calibrated models on their ability to estimate yield potential for major rice-maize cropping systems in Indonesia.

2. Materials and methods

2.1. ORYZA and Hybrid Maize models

ORYZA is a crop model that simulates rice growth and development (Kropff et al., 1993; Bouman et al., 2001; Li et al., 2017). Briefly, the model simulates CO_2 assimilation and respiration on a daily basis. Daily net carbon assimilation is estimated by difference and allocated to roots, stems, leaves, and panicles, with partitioning coefficients dependent upon developmental stage. For simulating Yp, ORYZA assumes no limitations by water and nutrients and an absence of insect pests, weeds, and diseases. ORYZA has been used to simulate Yp across major rice producing areas in the world (*e.g.*, Espe et al., 2016; Guilpart et al., 2017a,b; Stuart et al., 2016; Yuan et al., 2017). The latest version of ORYZA (ORYZA V3) has been released recently, with an improved capability to simulate rice growth and yield across a wide range of environments (Li et al., 2017). ORYZA requires calibration of six coefficients to account for cultivar differences in phenology: development rates for juvenile (DVRJ), photoperiod-sensitive (DVRI), panicle development (DVRP), and reproductive phases (DVRR), photoperiod sensitivity, and maximum optimum photoperiod. Another set of coefficients related to dry matter partitioning at different crop stages also requires calibration. Consequently, calibrating ORYZA for a given variety requires detailed experimental data (dates of heading, anthesis, and physiological maturity, leaf area index [LAI], and dry matter production and partitioning), management practices (plant density and dates of sowing and transplanting), and daily weather data, including solar radiation and maximum (T_{max}) and minimum temperature (T_{min}).

'Hybrid Maize' simulates maize growth and development for rainfed and irrigated conditions (Yang et al., 2004, 2017). Hybrid Maize is similar in structure to ORYZA, but only requires a single genotype-specific input parameter: growing-degree days (GDD) from crop emergence until the crop reaches physiological maturity. All other parameters governing photosynthesis, respiration, leaf area expansion, light interception, biomass partitioning, and grain filling are considered to be stable across modern maize hybrids. For estimating Yw in rainfed crops, Hybrid Maize accounts for water supply amount and distribution as well as soil properties influencing crop water availability such as soil texture, soil depth, and field slope. The model has been satisfactorily evaluated on its ability to reproduce observed yields in well-managed experiments that portrayed a wide range of rainfed and irrigated environments, with yield ranging from near crop failure to 18 Mg ha^{-1} (Grassini et al., 2009; Yang et al., 2017). Hybrid Maize has been used across many countries with diverse climate and soils to estimate Yp, Yw, and yield gaps,[2] determine yield goals to estimate nutrient requirements, and evaluate management options (Witt et al., 2006; Timsina et al., 2010, 2011; Grassini et al., 2011; Setiyono et al., 2011; Chen et al., 2011, 2013; Meng et al., 2013; Schulthess et al., 2013; van Ittersum et al., 2016). However, an explicit evaluation of Hybrid Maize's ability to reproduce Yp and Yw of maize in the humid tropics is lacking.

2.2. Databases for model calibration and evaluation

2.2.1. Rice experimental data

Two sources of experimental data were used for rice: (i) high-yield (HY) experiments conducted by the Indonesian Center for Rice Research (ICRR) and (ii) ICRR's multi-location cultivar evaluation

[2] Yield gap is defined as the difference between Yp for irrigated crops (or Yw for rainfed crops) and average farmer yield (van Ittersum et al., 2013).