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Estimation of separate effects of water and nutrient limitation for rainfed lowland rice within a province in the Mekong region

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ABSTRACT

Drought and low soil fertility are major constraints for high yield in rainfed lowland rice in Laos. To examine the separate effects of low water and nutrient availability and then to provide regional-scale fertilizer recommendations for rainfed lowland rice, a simulation study, together with field measurements, was carried out for Savannakhet province in the 2007 and 2008 seasons. To achieve this, a soil nutrient model QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) was combined with a recently developed soil water balance (SWB) model. The nutrient model was used to estimate yield from N, P and K uptake under various supply of nutrient in the soil, and then yield reduction due to water stress was calculated from the water balance model. The combined model was validated with the yield results of field experiments conducted in the dry season with no water limitation and also with yields obtained from 101 farms across the province in two wet seasons where both water and nutrient may have been limiting yield. The yield under inherent nutrient supply without fertilizer input was calculated from soil organic carbon, available P and K, and pH, and without water limitation, and was estimated to range widely between 1 and 2 t ha^{-1} for the central Lao province of Savannakhet. Yield was estimated to increase on average from 1.6 t ha^{-1} to 2.9 t ha^{-1} with the recommended fertilizer application rate of 60–13–16 N–P–K kg ha^{-1}, and up to around 6 t ha^{-1} under non-limited nutrient conditions. Yield reduction due to water stress alone, estimated from the soil water balance model, was 4–12%. These results indicate that the influence of water stress on the yield estimated for the two wet seasons was rather small, compared with that of nutrient stress. Fertilizer rates to achieve a particular yield target, which were calculated by subtracting inherent nutrient supply from nutrient uptake required for the yield target and then dividing by fertilizer nutrient taken up per kg applied, were also estimated to determine the variability of nutrient requirements at different locations. In most of the rice-growing areas, nitrogen, phosphorus and potassium required to achieve the yield target of 3 t ha^{-1} varied widely between 20 and 70 kg ha^{-1}, 5 and 35 kg ha^{-1} and 10 and 30 kg ha^{-1}, respectively, suggesting the importance of utilizing the site-specific fertilizer recommendation for rainfed lowland rice.

1. Introduction

In rainfed lowland rice environments, crop performance is variable among fields due to differences in field hydrology, inherent soil fertility and crop management practices, and it is also unpredictable due to variable rainfall patterns. Crop simulation models can be utilized to evaluate separate effect of these factors on grain yield. Currently there are large differences in the scope and complexity of crop models including rice models that are used to estimate crop yield. The existing rice models like CERES-Rice (Ritchie et al., 1986) and ORYZA2000 (Bouman et al., 2001) use complex functions describing water balance to estimate crop water availability, crop response to nutrients, and radiation penetration into crop canopies to provide an estimate of canopy photosynthesis and eventually yield in rice. Models that are useful for crop yield estimation commonly need to include a minimum of five interacting modules: duration of crop growth, biomass growth rate, the partitioning of biomass produced particularly to the economic yield component, soil water balance, and nutrient uptake and balance in the soil (Ritchie, 1990). There appears almost no rice model that estimates fertilizer requirement under different water availability conditions for rice, particularly using rather limited soil information as inputs.

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Fertilizer requirement and water availability of rainfed lowland rice in the Mekong region including Laos was recently reviewed by Fukai and Ouk (2012). In the Mekong region where rice is grown mostly as rainfed lowland rice and soil information is rather limited, soil fertility is generally low, and water availability varies greatly geographically within a province as well as in different seasons (Inthavong et al., 2012).

The water balance component is important for model development, as insufficient water during crop growth is considered to be one of the most serious problems limiting the productivity of rainfed lowland rice in the Mekong region (Fukai and Ouk, 2012). Lilley and Fukai (1994) stated that water deficit imposed during the reproductive period can reduce grain yield by 20–70%, with reduced growth rate during panicle development reducing both grain number and potential grain size. Ouk et al. (2006) from their work in the Mekong region, reported that the yield reduction caused by water stress increased as the free water level at around flowering (i.e. water level three weeks before and after flowering time) decreased below the soil surface. They used this water level as an index of the severity of water deficit when estimating yield reduction. A soil water balance (SWB) model was developed by Inthavong et al. (2011b) which used estimation of deep percolation loss from soil clay content under soil water saturation together with estimation of other components of water balance in lowland fields. The results from field experiments in Laos reported in Inthavong et al. (2011a) were used to validate the model, and spatial variation in water availability and hence the length of the rice growing period within the central Lao province of Savannakhet was estimated. The estimated length of growing period for Savannakhet was found to vary greatly, and depended on soil clay content and rainfall particularly late in the season which affected the time of the end of the growing period (Inthavong et al., 2012).

Apart from water, soil nutrients and fertilizer application management strongly determine rice yield in the region. With increased use of high-yielding varieties with an increased demand for nutrients, fertilizer inputs have increased in the rainfed lowland rice environment. This is reflected in Laos, where it is acknowledged by farmers that improved crop productivity cannot be met by either inherent nutrient supply or by ‘organic farming’ alone (Linquist and Sengxua, 2001). The site-specific nutrient supply is an important key to improving rice productivity (Dobermann et al., 2002, 2003). To improve fertilizer use efficiency, a quantitative understanding of crop nutrient demand and inherent nutrient supply from the soil, and the supply from chemical fertilizer, are required for site-specific fertilizer management. The approach for estimating quantitative inherent soil nutrient supply developed by Janssen et al. (1990) and site-specific nutrient requirement by Dobermann and Cassman (2002) and Witt and Dobermann (2002), is widely used for assessing soil fertility and chemical fertilizer application requirement for maximizing yields under different soil conditions (Bindraban et al., 2000; Dobermann et al., 2003; Pathak et al., 2003).

The objective of this study was to estimate the separate effect of nutrient and water limitation on yield of rainfed lowland rice and to provide regional-scale fertilizer recommendations for rainfed lowland rice. To achieve this, two already well developed soil nutrient and water balance models were combined and validated in the present study, and used for Savannakhet province in Laos.

2. Materials and methods

2.1. Study area

The study focused on rainfed lowland rice areas in Savannakhet Province in the lower central agricultural region of Laos (15°50′–17°10′ N, 104°40′–106°50′ E). The central and western parts of the province consist of a wide floodplain adjacent to the Mekong River, so most of the land used for growing rice is located in the western half of the province. The province has a monsoonal climate, with the southwest monsoons being associated with distinct wet (May–October) and dry (November–April) seasons. Dominant topsoil texture types are coarse-textured, sand (<5%), sandy loam (38%) and loamy sand (41%), while clay loam and loam texture groups account for less than 20% of the total area of the province; in subsoil layers, sandy loam and clay loam soil textures account for 36% and 31% of the total area, respectively (SSLCC, 1996).

2.2. Model description

Both the soil nutrient model and water balance model used in the current study have been published and hence only brief descriptions of these are given below. The model used here has combined these two component models.

A modified version of QUantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) developed by Janssen et al. (1990) was used to assess nutrient-limited yield of rice (Witt et al., 1999). The model calculates yield as a function of available soil nitrogen (N), phosphorus (P) and potassium (K) and the procedure of the calculation method is described in detail in Witt et al. (1999). The approach for site-specific nutrient management developed by Dobermann and Cassman (2002) and Witt and Dobermann (2002) was incorporated into this module for the estimation of fertilizer rates to be applied for achieving the grain yield target (e.g. $4\,\mathrm{t\,ha^{-1}}$). The amount of fertilizer needed to produce the target yield [fertilizer requirement (FR, $\mathrm{kg\,ha^{-1}}$)] can be calculated by subtracting the amount of nutrient available in the soil [inherent nutrient supply (N_{ind}, $\mathrm{kg\,ha^{-1}}$)] from the amount of nutrient needed to produce the yield target [nutrient uptake required for the yield target (NU_{target}, $\mathrm{kg\,ha^{-1}}$)], and then divided by the recovery efficiency of applied nutrient (RE, kg fertilizer nutrient taken up per kg applied):

$$\mathrm{FR} = \frac{\mathrm{NU_{target}} - \mathrm{N_{ind}}}{\mathrm{RE}} \tag{1}$$

The required nutrient uptake is provided by Witt et al. (1999); $15\,\mathrm{kg\,N\,ha^{-1}}$, $2.6\,\mathrm{kg\,P\,ha^{-1}}$ and $15\,\mathrm{kg\,K\,ha^{-1}}$ would be needed to produce 1000 kg of rice grain per ha until yield reaches 70–80% of potential yield. The inherent N supply is estimated based on an equation by Janssen et al. (1990), while modified models by Mulder (2000) were used to determine the inherent supply of P and K. The recovery efficiencies used in the present study were 0.5 for N, 0.2 for P and 0.45 for K; Witt and Dobermann (2002) reported 0.4–0.6, 0.2–0.3 and 0.4–0.5 for N, P, and K, respectively, for irrigated lowland rice.

The soil water balance (SWB) model was developed and validated with a range of free water levels. Free water levels were determined weekly during crop growth by installing a perforated PVC tube in the paddy field (Inthavong et al., 2011b). The SWB model estimates the amount of water stored in a soil profile that is divided into the surface soil (0–20 mm) and subsoil (200–1000 mm) layers. The components of the SWB model in the surface layer are rainfall, evapotranspiration (ET), downward water loss and runoff, while those in the subsoil layer are downward water loss into deep soil and the water gain from the surface layer. The FAO crop coefficient approach was used to estimate ET, and the downward water loss was estimated from an empirical relationship with soil clay content. The model has been described in detail and validated elsewhere (Inthavong et al., 2011b). The relative water level ($\mathrm{WL_{REL}}$) was determined by taking the mean of free water level around flowering time only when free water level was below the soil surface (Ouk et al., 2006). In the present study, the flowering date for each genotype group was defined by using ‘days-to-flower’ collected from more than 30 genotypes grown in field experiments