문서번호 APCC-출장-16-0060(2016-01-26)

결재	선임연구원	팀장	부서장	원장
	01/26 김대하	01/26 김옥연	01/26 김형진	01/26 정진승
협조				

TRAVEL REPORT FORM
출장보고서

I. Reporter

Department	Position	Name	Travel Date	Note 비고
Climate Research Department	Research Fellow	Daeha Kim	2016.1.17.-23.	

II. Major Activities

1. Main Contents and Activities

○ The objective of travel: To find potential end-user's demands in order to scope the APCC-IRI co-project for rain-fed rice productivity in Laos

○ Meeting schedules
- Meeting at the Department of Meteorology and Hydrology (DMH): Jan, 18th
- Meeting at the National Agricultural and Forestry Research Institute (NAFRI): Jan, 19th
- Meeting at the Department of Agriculture (DOA): Jan, 20th
- Follow-up meeting with IRI, CIAT, and IRRI: Jan, 21th

○ APCC and IRI's participants: Daeha Kim and Dr. Simon Mason (the chief climate scientist)

○ Local participants:
- DMH: Mr. Bounteum Sysouphanthavong at DMH (Head of Weather Forecasting Division),
Mr. Viengxai Manivong (Head of Planning and Cooperation Division)
- NAFRI: Dr. Thavone Inthavong (Director of NAFRI)
Dr. Vanthong Phengvichit (Deputy Director General of NAFRI)
- DOA: Mr. Khamtanh Thadavong (Deputy Director General of DOA)
Mr. Viengsavay Sengsurivong (Director of Standard Division)
Mr. Salongxay Rasabud (Deputy Director, Division of Planning and Cooperation)

○ Keypoints of the meetings:
- The potential end-users confirmed that 80% of population in Laos are farming under rain-fed condition, and climatic variability is the first concern of policymakers.
- Climate forecasts for rainy season are very critical for Laos agriculture.
- Present food-security of Laos is unlikely to be vulnerable because of enhanced productivity, but climatic variability is a major risk source.
- Particularly, onset dates of the rainy season affects practical managements (e.g. preparing seedlings and scheduling planting dates), and thus are very critical for local farmers.
- NAFRI has its own crop model for yield forecast, but it is very simple and need to be improved.
- FAO's AquaCrop is a candidiate to be used for improved crop forecasting.
- From crop modeling, NAFRI wants to have more scientific analyses (e.g., relationship between climate and disease, and between climate and nutrient availability).
- Importantly, every potential end-user wants to have workshops and training programs for operational use of the climate and crop forecasts. Mr. Salongxay Rasabud, who processes every externally funded project for Laos, especially expressed the learning programs for operational use no matter what the topic is.
- It is administratively impossible for a senior researcher of IRI to have a six-month trip due to their tight schedules. They cannot have a sabbatical because they are not faculty member of the university. At maximum, one-month trip is possible, but objectives of the trip should be clearly

defined before their visiting

- For this co-project itself, it is not necessary for a senior research to visit APCC. Specialty of a senior researcher is broader than conducting a specific analysis such as scoping a project, linking between institutions, developing future studies, etc.

2. Relevance to APEC Climate Center’s Activities

○ Crop modeling with climate forecasts is a good topic for the potential end-users, but training programs and workshops are essential for operational use.
○ Demands for climate forecasts and crop outlook are very high.
○ AquaCrop can be the main tool for the project.
○ Relationship between climate and disease (or nutirent loss) are also their interests.
○ For inviting IRI’s senior scientist, how long and why to visit are appropriately decided. For this project itself, it would not be helpful because he/she is not a modeler.

III. References

(with attachment of any information or report in case of attendance of conferences, workshops and meetings)

1. Presented and Collected Materials

○ Literature on rice productivity in Laos
○ A report for climate change impact assessment (Development Strategy of the Crop Sector 2025 and Vision 2030, DOA)

2. Suggestions and Remarks

○ A conference meeting between APCC and IRI is needed to finalize the scoping mission.

The meeting at DMH

1. Time/place: 18Jan2016 10:00-12:00 @ Department of Meteorology and Hydrology
2. Participants:
   - Dr. Simon Mason of IRI
   - Dr. Daeha Kim of APCC
   - Mr. Bounteum Sysouphanthavong at DMH (Head of weather forecasting division)
   - Mr. Viengxai Manivong (Head of Planning and Cooperation Division)
3. Summary
   a. purpose: To discuss the co-project between IRI and APCC, predicting rain-fed rice productivity in Lao PDR and seasonal or sub-seasonal climate forecasts for policy-maker's decision making
   b. Impacts of the proposed project:
      - The two heads agreed to the importance of food-security in Laos although they are not the specialists for agriculture in Laos
      - Climatic variability is a main concern of farmers.
      - Currently, long-term climate change is less important to farmers, but DMH is being asked by various government departments to provide information on observed climate change. Climate change projections are the mandate of a separate ministry.
      - Importantly, the lower Mekong River Basin often suffers from floods, which affect the central and southern provinces.
      - The DMH has recently issued a drought alert. The previous monsoon season was below-average, although rainfall was fairly continuous and so the impacts on crops were not very serious.
   c. About climatic data and forecasts:
      - For crop modeling, daily climatic observations and forecasts are necessary
      - Some data are available and accessible in Laos, but dependent on where the target area is.
      - The target area is changeable based on the data availability. No specific area is currently targeted.
      - Need to have a meeting with NAFRI and DOA first. Crop models require phenological and soil data for calibration and validation. Both data sets are also important.
      - When using climate forecasts, spatio-temporal downscaling will be implemented. The downscaled climatic forecasts would be good for other purposes, e.g. disaster warning system.
      - Currently, DMH is building the national early warning center for disaster and health management. Climate forecasts are also meaningful for the center. (The center will be built this year)
      - DMH has performed some analyses of changes in temperature, but there are no reports currently available, and other variables have not been analyzed. It may be beneficial to assist DMH to develop a small selection of observed climate change information notes.
      - DMH is interested to develop its existing climate forecasts in the following ways:
        i) Improved use of APCC multi-model products, perhaps starting with model SST forecasts as predictors in their current forecast system
        ii) Provision of onset date information
        iii) Tailoring of seasonal forecasts to predict parameters with a closer relationship to crop yields than the seasonal total rainfall.

d. Some demands from DMH

- Training program for using products of the project operationally
- Help to construct or improve infrastructure for climatic observations (instrumentation)
- Some literature on agro-meteorology for use in training workshops

The meeting at NAFRI

1. Time/place: 19Jan2016 09:30-14:30 @ National Agriculture and Forestry Research Institute
2. Participants:
   - Dr. Simon Mason of IRI
   - Dr. Daeha Kim of APCC
   - Dr. Thavone Inthavong (Director of NAFRI)
   - Dr. Vanthong Phengvichit (Deputy Director General of NAFRI)
3. Summary
   a. purpose: To find potential end-user's demands and requests on climate and agricultural forecasts and the proposed project
   b. Information and opinion from NAFRI:
      - Approximately 80 percent of population works for rice production under rain-fed condition.
      - Dr. Thavone confirmed the importance of climate forecasts for scheduling management practices for rain-fed rice cropping (e.g., timing of seeding and transplanting). Particularly, the onset of rainy season is critical for preparing seedlings.
      - Rain-fed rice planting in Laos begins with transplanting seedlings while direct seeding is common in irrigated farms. Transplanting can improve productivity, but require more water at the early stage. The onset of rainy season, hence, is valuable information for practical management.
      - The biggest climatic risk in Laos is non-stationary high spatial variability of precipitation, while variability of temperature seems to be insignificant and relatively stationary.
      - Properties of the rainy season are significantly changing inter-annually (e.g., onset, length, total precipitation)
      - Farmers have experienced floods and droughts every year.
      - NAFRI has its own crop model albeit very simple, and thus is able to make their own crop yield forecast as long as climate forecasts are given.
      - Currently, NAFRI uses modeled water stress at the flowering stage as a predictor of crop yield.
      - Crop ground observations (yield, LAI, etc.) from experimental plots are available for calibration and validation of the crop model for rain-fed rice.
      - NAFRI tried to use DSSAT for yield forecasting, but experienced overestimation in crop yield. It is not in use now
      - FAO AquaCrop was also used for crops in non-rainy season, but not for rain-fed rice.
      - NAFRI's first priority for agricultural practices is precise climate forecasts. Crop modeling is not a key issue in practice because of a gap between mathematical formulations of models and actual plant reponses.
      - From crop modeling, NAFRI wants more scientific results (e.g., relationships between climate conditions and/or between climate and nutrient loss).
      - NAFRI's difficulty to use climatic data is low spatial density of climate stations in rural areas. The gap between observation and dissemination of data is also notable. In order to use climate forecasts for crop outlook, field-scale precipitation and temperature data are necessary. Thus, downscaling and interpolation are essential.
      - NAFRI's current main interest regarding climate and agriculture is short-term (inter-annual, seasonal, or sub-seasonal) variability of climate rather than long-term projections of climate change.

- Importantly, NAFRI is about to found the center of climate resiliency in agriculture
- Scenario analyses in regard of management practices (e.g., yield response to planting timing) would be beneficial for NAFRI.
- Policymakers are very interested in changing cropping patterns for reducing climatic risk on agricultural production (e.g., rotation of crops, plating cash crops, etc.). Scenario analyses with crop models would be good information.
- Agricultural productivity of Laos has improved for last two decades, but still needs more improvement when compared to neighbor countries. Present national food security seems to be good.

c. Comments of Dr. Vanthong Phengvichit

- Farmers just know seasonal variation of climate in Laos from their experience. Detailed information about climate and agriculture including forecasts is very helpful
- NAFRI has several teams for Ago-bio diversity, improving agricultural productivity, climate change, supporting agricultural policy, and so forth.
- For supporting policymakers' decision making, many hypotheses should be answered with scientific analyses. Technology and informatics are very important.
- Data sharing even between government departments of Laos is not easy. This project can be a bridge between the departments for data sharing.
- Workshops for sharing technology are needed, but limited in NAFRI. It is critical for a successful project.
- There is no problem to provide letters of MOU from NAFRI. More important thing is to improve agricultural practices and reduce climatic risk.

The meeting at DOA

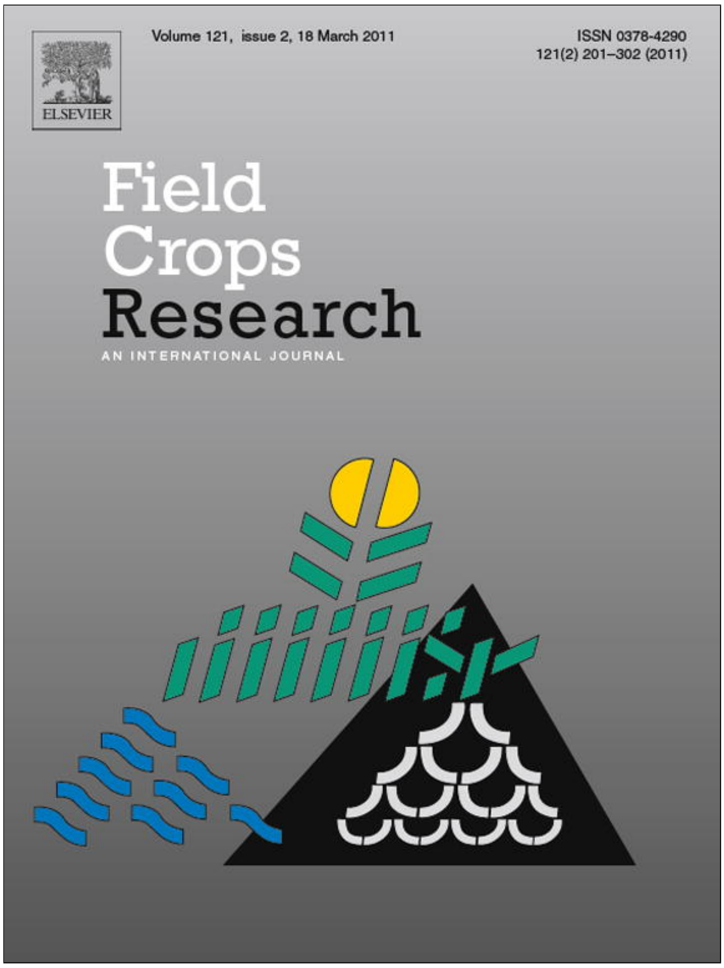
1. Time/place: 20Jan2016 14:00-15:00 @ Department of Agriculture
2. Participants:
   - Dr. Simon Mason of IRI
   - Dr. Daeha Kim of APCC
   - Dr. Thavone Inthavong (NAFRI)
   - Mr. Khamtanh Thadavong (Deputy Director General of DOA)
   - Mr. Viengsavay Sengsurivong (Director of Standard Division)
3. Summary
   a. purpose: To find requests of potential end-users in a broader point of view
   b. Information and opinion from DOA:
      - Climate change is one of main issues in Laos like other countries, and there is a potential project in collaboration with FAO.
      - Policymakers' interests are climate change, flood and drought and floods, disaster management, etc.
      - Sometimes 150,000+ ha are affected by climatic variability.
      - DOA can provide agricultural statistics in Laos.
      - Disease monitoring and control are an important issue related to climate conditions.
      - Countermeasures for diseases are prepared, but it is difficult to decide when and where to use them. Climate forecasts would help to overcome the difficulty.
      - IRI will investigate more details about the relation between climate and disease
      - Products from this project should be provided in a timely manner
      - FAO did crop modeling about 15 years ago for main cropping areas
      - Crop forecasts with RS images are produced in cooperation with the Ministry of Science and Technology of Indonesia.
      - Some climate change impact assessments are already carried out.
      - How to achieve spatial variability of precipitation is the key point due low density of the gauging network.
      - DOA generally confirmed importance of climate forecasts and relationship between climate and crop productivity in Laos.

The meeting at Division of Planning and Cooperation

1. Time/place: 20Jan2016 15:00-15:35 @ division of planning and cooperation
2. Participants:
   - Dr. Daeha Kim of APCC
   - Dr. Thavone Inthavong (NAFRI)
   - Mr. Salongxay Rasabud (Deputy Director, division of planning and cooperation)
3. Summary
   a. purpose: To find requests of cooperation division
   b. Information and opinion from DPC:
      - The deputy director generally agreed to importance of climate forecasts and crop outlook.
      - A major concern is whether or not products of this project are operationally useful.
      - Currently, human resource of DOA is very limited for operational use of outcomes from the project. One of the most important things is training programs for using the products.
      - The director advised that it would be important to take into account training programs when developing a proposal. Projects for only articles are not desirable.

Suggestions of Dr. Kim and Mason

1. Training program for operational use of products from this project (e.g., data access, sharing, and distribution, downscaling climate data, description of crop models, etc.) should be included.
2. Demand of mapping spatial distribution of precipitation across the nation is very high.
3. Crop modeling with a sophisticated model is not desirable. Capacity of NAFRI to handle a complex model is inadequate. Simple approaches are suitable.
4. Onset of monsoon is the key information from climate forecasts.
5. In regard of crop modeling, finding relations between climate and disease, and/or between climate and nutrient loss are additional topics in high demand
6. Simple approaches for downscaling and crop modeling are better for Laos
7. Precipitation estimates from remotely sensed images would be usable as an alternative for data limitation
8. Due to low predictability of precipitation in Monsoon season, forecasts on onset dates would be good for operational use.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A water balance model for characterization of length of growing period and water stress development for rainfed lowland rice

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ABSTRACT

There is large year-to-year variation in rice production across the Mekong region (Laos, Cambodia and Thailand) due to uncertainty in the timing of the onset of the wet season and drought stress that may develop at any time during the growth of rainfed lowland rice. Unique to the nature of lowland water balance is a large component of deep percolation water loss, which depends on soil texture. The objectives of this study were to develop a soil water balance model for calculating the amount of water held in field storage (i.e. in soil and, if there is standing water, above the soil surface) and to apply it to determine the length of growing period (LGP) and water stress development in relation to soil type and rainfall pattern for the rice ecosystem. The water balance is computed separately for above-ground plus topsoil layer and subsoil layer. Components of the water balance are the existing amount of stored water, rainfall, evapotranspiration, deep percolation, and runoff. The deep percolation rate was determined from clay content in each soil layer. The model runs with daily or weekly weather data to estimate the soil water level for the growing period in the wet season. The model was validated with data collected from top, middle and bottom of rainfed lowland fields in Savannakhet province, Laos. The best correlation between the observed and simulated water level was obtained ($r^2 = 0.41$) for middle fields. The simulation results showed that LGP varied greatly from year to year, particularly in locations with sandy soils, due mostly to variation in monthly rainfall occurring at the early part of the growing season (April), but also to some extent by variation at the end of growing season (October). Soil texture on the other hand is shown to have a large influence on the end of the rice growing period and hence LGP, and also water stress development during growth. Sandy soils with clay content less than 7% that are prevalent in the province are shown to cause frequent water stress and early finish in rainfed lowland rice. The model accordingly provides reasonable outputs that can provide a geographical dimension of soil hydrological patterns for various rice growing environments, and also identify the spatial pattern of drought stress that is likely to occur. Model outputs can be used to provide guidelines for practical advice to the rice farmers and researchers for determination of appropriate crop management strategies (e.g. time of planting, varieties), and policy makers for investment decisions on inputs (e.g. fertilizer price) aimed at increasing rice productivity in this Mekong region.

1. Introduction

Rainfed lowland rice (*Oryza sativa* L.) is defined as rice cultivated in fields surrounded by bunds under rainfed conditions, with standing water for at least part of the growing season. This type of rice ecosystem is dominant in the wet season in the Mekong region (Mackill et al., 1996; Wade et al., 1999). Rainwater is the only source of water input to the rice fields, and water stress can often affect crop growth during the growing season, particularly late in the season. In the central and southern regions of Laos, adverse water conditions are regarded as the major production constraint in the lowland rice environment (Inthapanya et al., 1996). Two major problems are encountered by rice producers in relation to the water environment during the period of wet-season cropping in the region: (i) uncertainty in relation to the timing of the onset of the wet-season rains, and the effects of this uncertainty on timely sowing and transplanting; and (ii) potential late wet-season drought, which can affect the reproductive stage of plant growth and grain yield. As a result, there is considerable year-to-year variation in rice production in the region. A large spatial variation in

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yield can occur, partly reflecting the variability of the clay content of the soils, such as occurs in the central part of Laos where more than 60% of the total agricultural land area consists of soils with a clay content below 12%. The low and variable clay content is reflected in large variation in water availability, with resulting low grain yields in rainfed lowland rice crops. At individual locations such as in Outhomphone district of Savannakhet province where the clay content of lowland rice soils is less than 5%, grain yield ranged from 1.1 to 1.8 t ha^{-1} (Manivong and Douangsavanh, 2007). Jongdee et al. (2006) also report that yield losses due to water stress in rainfed lowland rice crops of neighbouring Northeast Thailand can range from 11 to 58%.

Water balance modelling is an accounting of the inputs and outputs of water in a system. Generally, in rainfed lowland rice fields, the major input of water is from precipitation, with the rainwater then potentially moving along one of several pathways. The water may be removed by evaporation and transpiration. It can percolate through the soil profile to ultimately become aquifer recharge; on sloping land, it may also move laterally. In most rice crop models, for example, RICEMOD (McMennamy and O'Toole, 1983), CERES-Rice (Singh et al., 1993), RLRice (Fukai et al., 1995) and ORYZA2000 (Bouman et al., 2001), the soil water balance is calculated to evaluate possible yield reductions caused by soil and plant water deficits. The water balance sub-model calculates water loss through transpiration, soil evaporation, deep percolation and lateral water movement, to determine plant extractable soil water content. The productivity of rainfed lowland rice could be improved, once the water availability during the growing period is quantified for different rice growing areas. For example, use of certain varieties and cultural methods (e.g. quick maturing varieties, direct seeding rather than traditional transplanting) may be considered for adoption to minimize the risk of lack of standing water in the field.

For areas with low clay content soils, the development of a field water balance model that can accurately estimate the components of water loss, particularly through downward and deep percolation, is considered important for characterizing the water environment. The downward water loss (*D*) is a main determinant of water availability in a paddy field; it is affected by a variety of environmental and soil-related factors including soil texture, structure, conductivity of the different layers, subsoil water content, ground water depth and standing water level above the soil surface (Khepar et al., 2000). A trend of decreasing field water availability and an increasing number of days without ponded surface water, associated with downward and lateral water movement from the top of a toposequence, a series of paddy fields on a sloping land, has consistently been found in soils with low clay content in the paddy fields of Indonesia and Thailand (Boling et al., 2008). Field experiments in Northeast Thailand and Southern Laos have showed that downward water loss and lateral water movement are negatively correlated with the soil clay content (Fukai et al., 2007; Tsubo et al., 2007a), such that soil texture, particularly clay content, can be used to determine *D* for lowland fields. Even though paddy water balance has been studied widely for both rainfed and irrigated environments, only a few studies have characterized the vertical downward water movement, a large component of water balance in paddy fields in a wide range of soil types. Some models that are currently available compute the component of percolation flow by using hydrostatic water pressure which is estimated from the depth of free water (Bouman et al., 2001). Other models, such as the water balance model for paddy fields under intermittent irrigation practices, calculate deep percolation losses based on saturated and unsaturated conditions of the fields (Khepar et al., 2000). Most lowland models require data relating to soil water transmission characteristics (e.g. soil hydraulic conductivity and soil water storage properties), which may not be readily available for a large area with varying soil texture.

The objectives of this study were to develop a soil water balance model that incorporates the effects of low soil clay content on deep percolation and to estimate the length of growing period and water stress development during growth in relation to soil type and rainfall patterns using selected sites in southern Laos as an example. The soil water balance model developed in the study was designed to determine the capacity of a soil to maintain standing water in the paddies, by using an empirical relationship between soil clay content and downward water loss. The model was validated with data collected from rainfed lowland rice fields in Savannakhet province, Laos. Simulation exercise was then carried out to investigate the effect of soil texture, particularly clay content, together with rainfall variability in different years.

2. Model description

2.1. Soil profile

The field water balance model was developed to estimate the amount of water stored in a soil profile, the profile being divided into two layers: (i) the surface soil layer (Layer 1: 0–200 mm) and (ii) the subsoil layer (Layer 2: 200–1000 mm). Layer 1 is the zone immediately above the hardpan created in the process of puddling. This layer is regarded as the effective root zone depth for lowland rice where water is taken up. Most roots are distributed within the surface soil (0–200 mm) under lowland conditions (Ghildyal and Tomar, 1982; Boonjung, 1992; Pantuwan et al., 2002). It is therefore assumed that crop evapotranspiration (ET_c) takes place only from Layer 1, with ET_c being strongly dependent on surface soil water content and the radiation load at the soil surface. The total amount of stored water in Layer 1 comprises the water above soil surface (i.e. standing water) plus water stored within the top 200 mm of soil. The total amount of stored water in each soil layer is calculated consecutively [i.e. first, water stored in the surface layer ($W_{surface}$), and then stored water in the subsoil layer ($W_{subsoil}$)], as follows:

$$\text{Layer 1}: \quad W_{surface(t)} = W_{surface(t-1)} + RF_{(t)} - ET_{c(t)} - D_{topsoil(t)} - RO_{(t)} \tag{1}$$

$$\text{Layer 2}: \quad W_{subsoil(t)} = W_{subsoil(t-1)} + D_{topsoil(t)} - D_{subsoil(t)} \tag{2}$$

where RF is rainfall, $D_{topsoil}$ and $D_{subsoil}$ are downward water loss from the topsoil and subsoil layers, respectively, RO is surface runoff, and t is time (e.g. day, week). Therefore, the total stored water in a soil profile (surface and subsoil layers) is represented by:

$$W_{total(t)} = W_{surface(t)} + W_{subsoil(t)} \tag{3}$$

In general, during the dry-season rice fields are dry at the soil surface, and there is a large soil water deficit in the profile. At the beginning of the wet-season, the surface soil water content can be equal to soil water content at air-dry conditions (S_{w_airdry}), while the initial subsoil water content at the beginning of the cropping season is assumed to be equal to subsoil water content at wilting point ($S_{subsoil\_WP}$). This is incorporated in the model as 'initial soil water content' for each simulation run, although the model could run from any time of the year with given soil water inputs, e.g. measured soil water content at time of transplanting. All the components of water balance are computed for the same point in time.

2.2. Water balance components

2.2.1. Crop evapotranspiration

The FAO crop coefficient approach (Allen et al., 1998) was employed to estimate the total ET. First, reference evapotranspiration (ET_o) was computed using the FAO Penman-Monteith equation, and then ET_c was calculated using a crop coefficient (K_c) and a water stress coefficient (K_s), as follows:

$$ET_c = K_s K_c ET_o \quad (4)$$

In the model, the effects of the various weather conditions (e.g. solar radiation, wind speed, humidity and temperature) are incorporated into ET_o, while crop characteristics and water stress conditions are incorporated into K_c and K_s respectively. In general, ET_c of lowland rice is dominated by water stress, and when soil surface is wet, ET_c is little affected by crop growth stages, and hence a constant value for K_c is used throughout the growing season. In addition, duration of each growth stage is not quantified in this study. The K_c value used for this study (K_c = 1.1) is the average of values provided by Allen et al. (1998) for the initial stage (K_c = 1.05), development stage (K_c = 1.2) and late-season stage (K_c = 0.9).

Loss of standing water does not affect ET_c when soil water conditions are favourable. The value of K_s is assumed to be equal to 1.0 when the soil water content in the surface layer is greater than field capacity. As soil water content in the root zone (surface layer) decreases to wilting point, rice crops will experience severe water stress but may survive for a period of time. If no additional water is received in the field, the soil will dry out and reach air-dry conditions, at which point the crop is assumed to die. The soil water deficit reduces the ET_c rate, and the proportion of stored water in the root zone ($W_{surface} - S_{W\_airdry}$) in relation to the total available water in the root zone ($S_{W\_FC} - S_{W\_airdry}$) is used to describe K_s, as in the following equation:

$$K_s = \frac{(W_{surface} - S_{W\_airdry})}{(S_{W\_FC} - S_{W\_airdry})} \quad (5)$$

where S_{w_airdry} and S_{w_FC} are the soil water contents under air-dry conditions and field capacity, respectively. When the soil surface becomes dry and the water content is below the air-dry status ($W_{surface} \le S_{w\_airdry}$), ET_c is assumed to be equal to 0 (K_s = 0) with no water left for soil evaporation and transpiration.

2.2.2. Downward water loss

Tsubo et al. (2007a) have developed an empirical relationship between the downward water movement ($D_{topsoil}$) and clay content of the topsoil above the hardpan (200 mm soil depth), when there is standing water in the field. The downward water loss rate was measured using a "percolator" which was constructed using a steel cylindrical tube 400 mm in length and 200 mm in diameter with a lid to prevent evaporation and exclude rainfall (Tsubo et al., 2005). The percolator was installed in the top soil slightly penetrating into the hardpan, so the meter could measure the vertical water movement through the hardpan. They used data collected from field experiments at six locations in Northeast Thailand, where the clay content of soil ranged from 4 to 47%. This relationship showed $D_{topsoil}$ decreased as the clay content of a soil profile increased (Tsubo et al., 2007b). In this study, the results from a number of additional field experiments conducted in two provinces (Savannakhet and Champassack) in Laos (Tsubo et al., 2006), and at the Cambodia Agricultural Research and Development Institute (CARDI) near Phnom Penh in Cambodia, were utilized. Using the datasets from the three countries, a regression relationship between clay content and the daily rate of $D_{topsoil}$ was developed (Fig. 1) and used in the present model by the equation below:

$$D_{topsoil} = \frac{18.7}{C} - 0.16 \quad (6)$$

where C is clay content in %. For sandy soils with clay content of less than 5%, $D_{topsoil}$ is estimated to exceed 3.5 mm day^{-1}.

Table 1 shows the estimated values of maximum downward water movement from the top soil ($Dmax_{topsoil}$) for different soil texture types for Savannakhet province (Laos) using the topsoil clay content range (0–200 mm soil depth) for each soil texture group, based on determinations from 15 clay loam samples, 41 loam samples, 124 sandy loam samples, 146 loamy sand samples, and 13 sand samples that were collected throughout the province. The downward water loss rates decreased as topsoil clay content increased (Table 1). For example, the estimated $Dmax_{topsoil}$ rate ranges from 0.3 to 0.7 mm day^{-1} for soils with a clay loam, and from 3.4 to 9.2 mm day^{-1} for the sandy soil. Soils with clay contents of 7–12% and 0–7% occupy 36.7% and 31.5% of the province area, respectively, so lowland rice growing areas in the province are mainly on soils with a clay content of less than 12%.

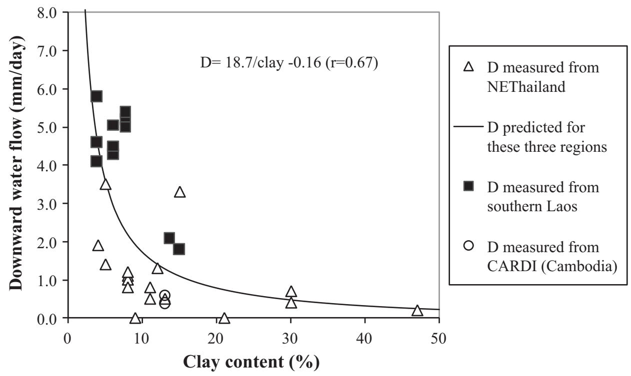

Fig. 1. The relationship of $D_{topsoil}$ and clay content in topsoil to a depth of 200 mm. The triangle, square and circle symbols refer to D measurements obtained in Northeast Thailand, Southern Laos, and CARDI (Cambodia) respectively. The solid line is the predicted D values for these three regions.

The downward water movement from the topsoil layer ($D_{topsoil}$) varies, reflecting the physical properties of the soil. $D_{topsoil}$ is assumed to decrease from $Dmax_{topsoil}$ linearly with the decrease in topsoil water content from S_{w_sat} to S_{w_FC}. The following three aspects of topsoil water content are used for the computation of $D_{topsoil}$.

$$D_{topsoil(t)} = Dmax_{topsoil} \quad \text{for } W_{surface(t-1)} = S_{w\_sat} \quad (7a)$$

$$D_{topsoil(t)} = Dmax_{topsoil}\left(1 - \frac{S_{w\_sat} - W_{surface(t-1)}}{S_{w\_sat} - S_{w\_FC}}\right) \quad \text{for } S_{w\_FC} < W_{surface(t-1)} < S_{w\_sat} \quad (7b)$$

$$D_{topsoil(t)} = 0 \quad \text{for } W_{surface(t-1)} = S_{w\_FC} \quad (7c)$$

Similarly, deep percolation losses from the subsoil layer ($D_{subsoil}$) are assumed to occur when the subsoil layer is fully recharged [i.e. when the subsoil water content is at saturation ($Sw_{subsoil\text{-}sat}$)]. Percolation loss plus lateral water movement from the subsoil layer is assumed to equal the maximum downward water loss from the top layer when the subsoil water content is saturated. The percolation rate is also assumed to decline linearly as the subsoil water content decreases. Therefore, $D_{subsoil}$ is estimated using the same approach as for the topsoil layer.

Table 1
Estimated maximum downward ($Dmax_{topsoil}$) water loss rate in relation to soil texture, for the topsoil layer (0–200 mm soil depth) in Savannakhet province, Laos. D calculated using Eq. (6).

Texture	Clay (%)	Estimated D rate (mm day^{-1})
Clay loam	21.3–40.0	0.3–0.7
Loam	5.8–25.4	0.6–3.0
Sandy loam	2.8–20.0	0.8–6.5
Loamy sand	2.4–10.0	1.7–7.6
Sand	2.0–5.2	3.4–9.2

2.2.3. Surface runoff

The model calculates water loss by runoff (RO) when the standing water exceeds the height of the bunds. The maximum amount of stored water (W_max) within surface layer is the sum of the water that saturates the topsoil (S_{w_sat}) and the bund height (h), expressed as:

$$W\_max = S_{w\_sat} + h \quad (8)$$

When $W_{surface(t-1)} + RF_{(t)} - ET_{c(t)} - D_{topsoil(t)}$ is greater than W_max, RO is calculated, as follows:

$$RO_{(t)} = W\_max - (W_{surface(t-1)} + RF_{(t)} - ET_{c(t)} - D_{topsoil(t)}) \quad (9)$$

Otherwise ($W_{surface(t-1)} + RF_{(t)} - ET_{c(t)} - D_{topsoil(t)} \leq W\_max$), there is no runoff.

2.3. Estimation of free water level

The free water level (WL) is estimated separately for three conditions. First, in the situation when the standing water disappears (WL ≤ 0), $W_{surface}$ in the surface soil layer (within 200 mm soil depth) may be reduced from topsoil saturation to wilting point. In order to estimate WL below the soil surface, it is assumed that the soil is saturated below WL (i.e. for the height of 200-WL mm) and the soil water content above WL is 50% of that at saturation. Soil water content of the combined layers is $W_{surface}$, and is expressed by the following equation:

$$W_{surface} = \frac{1}{2}\left(S_{w\_sat}\frac{WL}{200}\right) + \left(S_{w\_sat}\frac{200 - WL}{200}\right) \quad (10)$$

By rearranging the equation, WL below soil surface is as follows:

$$-WL = \frac{400(W_{surface} - S_{w\_sat})}{S_{w\_sat}} \quad \text{for } W_{surface} = S_{w\_sat} \quad (11a)$$

where a negative value (−WL) indicates that the free water level is below the soil surface. Secondly, when field stored water is greater than soil saturation (i.e. above soil surface) but not exceeding the bund height ($S_{w\_sat} < W_{surface} < h$), the standing water level is computed by subtracting S_{w_sat} from $W_{surface}$:

$$WL = W_{surface} - S_{w\_sat} \quad \text{for } S_{w\_sat} < W_{surface} < W\_max;\ 0 < WL < h \quad (11b)$$

The third conditions, when field stored water at surface layer ($W_{surface}$) is greater than the maximum amount of stored water (W_max), the depth of standing water is assumed to be equal to the height of the bund (h):

$$WL = h \quad \text{for } W_{surface} = W\_max \quad (11c)$$

2.4. Soil water characteristics and estimation of length of growing period

In this study, the model by Saxton and Rawls (2006) was used for estimation of soil water characteristics, i.e. volumetric soil water content at saturation ($\ominus_s$), field capacity ($\ominus_{33}$) and wilting point ($\ominus_{1500}$). The model is based on correlations between measured values for soil water characteristics and the variables of sand, clay and organic matter percentage, with the relationship then being adjusted for the effects of bulk density, gravel percentage and salinity. The volumetric soil water content under air-dry conditions used in the model was obtained from the information available for Northeast Thailand (Kam, 2000) which has soil physical conditions comparable to rice fields in the study area of Savannakhet, Laos. Table 2 gives the mean values of $\ominus_s$, $\ominus_{33}$, $\ominus_{1500}$, and air-dry within the topsoil (0–200 mm) and subsoil (200–1000 mm), for various soil textures. The estimated values come from a total of 339 soil profile samples in Savannakhet province for which the soil is deep, and consists of four master horizons (layers): A, AB, B_{ts1} and B_{ts2}, where subscript letters ts1 and ts2 signify an increase in accumulation of clay (t) and sesquioxide (s) properties in B_1 and B_2 horizon, respectively (SSLCC, 1996). Similarly, subsoil water characteristics were estimated from those deep soil profile samples.

Table 2
Various soil characteristics, sand and clay proportion, organic matter (OM), and volumetric soil moisture contents at soil saturation ($\ominus_s$), field capacity ($\ominus_{33}$), wilting point ($\ominus_{1500}$), and air-dry conditions, for topsoil layer (0–200 mm) and subsoil layer (200–1000 mm) for the dominant soil textures in Savannakhet province, Laos.

Soil texture type	Sand %	Clay %	OM %	$\ominus_s$	$\ominus_{33}$	$\ominus_{1500}$	Air-dry
(a) Topsoil layer				mm water per 200 mm soil depth			
Clay loam	38.8	32.5	1.8	84.7	63.4	38.9	11.6
Loam	41.8	15.9	1.3	77.8	45.7	19.5	6.0
Sandy loam	66.2	9.1	1.1	77.4	27.5	10.5	2.8
Loamy sand	82.6	6.2	0.8	79.8	17.1	6.2	1.9
Sand	88.2	4.5	0.7	81.6	12.8	3.8	1.0
(b) Subsoil layer				mm water per 800 mm soil depth			
Clay	26.7	44.2	0.86	374	314	210	–
Clay loam	52.9	25.4	0.61	319	204	122	–
Loam	45.8	18.1	0.62	311	185	88	–
Sandy loam	68.6	12.6	0.56	309	121	58	–
Loamy sand	81.5	7.3	0.47	317	75	30	–
Sand	87.6	4.2	0.39	327	51	14	–

The start to the growing period (SGP) is defined as the time when there is a period of three continuous weeks when the soil water content within the surface layer is greater than field capacity ($\ominus_{33}$). The end to the growing period (EGP) is defined as the time when soil water content within surface layer falls below wilting point ($\ominus_{1500}$). The calculations are done on a weekly basis, with the number of weeks showing stored water in the field being defined as the length of growing period (LGP).

In this study, the model was run to investigate which of the two main factors, soil texture or rainfall patterns, have a greatest impact on LGP. Comparisons of LGP were made by selecting two locations in the province, one representative of rice fields in the south and the other in the northwest, where the sites are: (1) similar in soil clay content but contrasting in rainfall pattern, and (2) similar in rainfall pattern but different soil clay contents, to investigate the separate effect of rainfall and soil type on LGP, respectively. The two sites chosen for the comparison of the effects of rainfall were the village of Kengping (16°00′N, 105°43′E) in Thapangthong district, and the village of Laophai (16°56′N, 104°54′E) in Xaibouri district. Both sites have soils with a sandy soil texture with a clay content of 5%, but with average annual rainfall of 1844 mm and 1334 mm for Kengping (the south) and Laophai (the northwest), respectively. In the second comparison for the study of the effects on LGP of soils with contrasting clay contents but similar rainfall, the villages selected were Nongkalong (16°33′N, 105°06′E) in Champhone district, and the village of Vangkhan (16°44′N, 105°04′E) in Outhomphone district. Both locations receive a similar annual rainfall (1539 mm and 1617 mm for Nongkalong and Vangkhan, respectively) but have soils with greatly contrasting clay content (4.8% in Vangkhan—sandy soil and 20.4% in Nongkalong—clayey soil).

The estimates of LGP for a series of individual years in the period 1985–2004 were used for frequency analysis of LGP for wet-season rainfed lowland rice planted in Savannakhet province. Year-to-year variation in LGP, including the SGP and EGP, was estimated for the villages of Thapho (16°22′N, 104°58′E) in Khanthabouri district and Seno (16°46′N, 104°59′E) in Outhomphone district. These two locations were selected, as long term rainfall data are available for both locations, and the locations have contrasting soil types; an average clay content of 9.3% in the Thapho village area and 3.8% in Seno. The rainfall pattern for the two locations is similar, although Seno has a slightly lower rainfall at the beginning of wet season (March–May). Weekly rainfall data recorded at the Savannakhet

(Khanthabouri district) and Seno Meteorological Stations for the period 1985–2004 was used to provide climate input, while the mean reference evaopotranspiration (ET_o) values estimated for the 5-year period 2000–2004 were used for these same locations. It was not possible to use ET_o data for a longer period than 5 years because of lack of input data for estimation of ET_o. A further reason for using the mean ET_o values was that the variation in weekly ET_o within years and across the province was relatively small, so the effect of ET_o on LGP would also be small.

Estimates were made of the LGP for individual years, and cumulative probability was then calculated. The interruptions of short drought events within the growing season (early season drought (between May and July); mid season drought (between August and September); and late season drought (between October and early November), were also investigated using soil water content. An intermittent water stress event was considered to begin when weekly field water storage declined below topsoil field capacity.

2.5. The effect of rainfall and soil texture types on LGP

A study was made of the model simulation of growing period responses to various soil texture types [sandy soil (SA), loamy sand (LS), sandy loam (SL), loam (L) and clay loam (CL)] in the topsoil layer, and in response to rainfall pattern, for rice fields in Khanthabouri district. For this exercise, the mean values of clay content (%) within the topsoil (0–200 mm) and subsoil (200–1000 mm) layers, and volumetric soil water content at $\ominus_s$, $\ominus_{33}$, and $\ominus_{1500}$ of those two layers, were estimated from soil profile samples taken from different rice fields (Table 2). Long-term weekly rainfall data for the period 1985–2004, obtained from the Savannakhet Meteorological Station, was used to estimate the growing period (start, end and length for each soil texture type).

3. Model validation

The model was validated with free water levels determined throughout rice growth at three toposequence positions across a large number of field experimental sites (48 sites) scattered across 7 districts (Atsaphanthong, Champhone, Khanthabouri, Outhomphone, Songkhone, Xaibouri, Xonbouri) within Savannakhet province during the wet season in 2008. The observed soil water data were described in (Inthavong et al., 2011). The soil of the field experiment sites in 2008 varied greatly from location to location ranging in clay content between 3.6% and 29.8% and between 7.2% and 40.1% for the topsoil and subsoil, respectively. Full sets of daily climatic data obtained from the Savannakhet Meteorological Station were used for computing ET_o, while daily rainfall data for the year 2008 from the period from transplanting (1 July) to near maturity time (the end of September) were collected using the rain gauges, for locations near the 13 field measurement sites. Thus the data sets covered a range of soil types and rainfall patterns. These were used as inputs to the model for estimates of stored soil water and field standing water level, during the period of growth of the rice. The model was run using the input of actual standing water level measured at transplanting time as the initial water level, with the bund height being set at maximum water level observed at each location. Linear regression analysis between measured and estimated water level, the average error (Bias), Root Mean Square Error (RMSE) and Index of Agreement (IA), to measure the degree to which the model's prediction was error free (Willmott, 1981) were used for quantitative assessment of a goodness of fit for the 7 districts in the 2008 wet season.

The results of the model validation with the field measurement data in 2008 showed that there was a good agreement between the observed and simulated results, for the free water level for the period after transplanting to maturity, for a number of locations in all 7 districts, and the results for mid toposequence position at three locations (i.e. Dornvai in Khanthabouri, Phonakhoun in Outhomphone and Houaysomnam in Xonbouri districts) are shown in Fig. 2 as examples of model simulated versus observed standing water level. For a number of locations, particularly sites at bottom toposequence position the simulated standing water levels differed greatly from the measured levels. These sites had unusual or extremely high standing water levels (e.g. water level increasing steadily until the end of the season even when there was no rainfall, probably as a result of the lateral water movement from the adjacent fields). These sites were excluded from further analysis. The relationship for the mid-toposequence position is shown in Fig. 3. The overall mean correlation as well as other indicators of model prediction over all districts indicated that the middle position water level was better predicted than the top and bottom positions in terms of bias, RMSE and IA (Table 3). Observed and simulated mean water level was below soil surface in the top toposequence position, while the middle position showed a mean of more than 25 mm

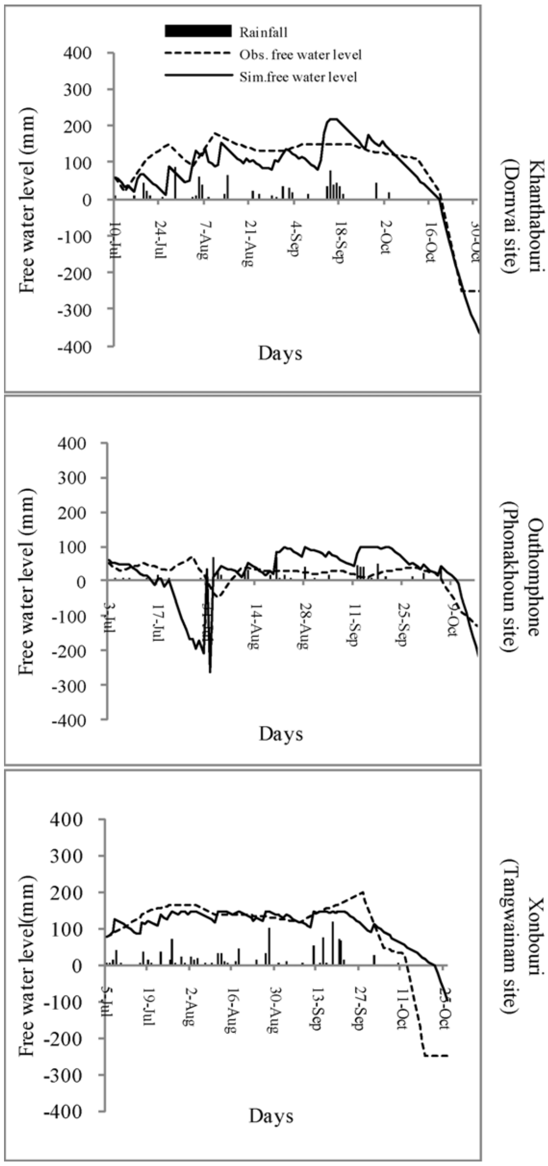

Fig. 2. Simulated and observed free water level (mm) for mid-toposequence position of rice fields in Khanthabouri, Outhumphone, and Xonbouri districts of Savannakhet province, Laos.

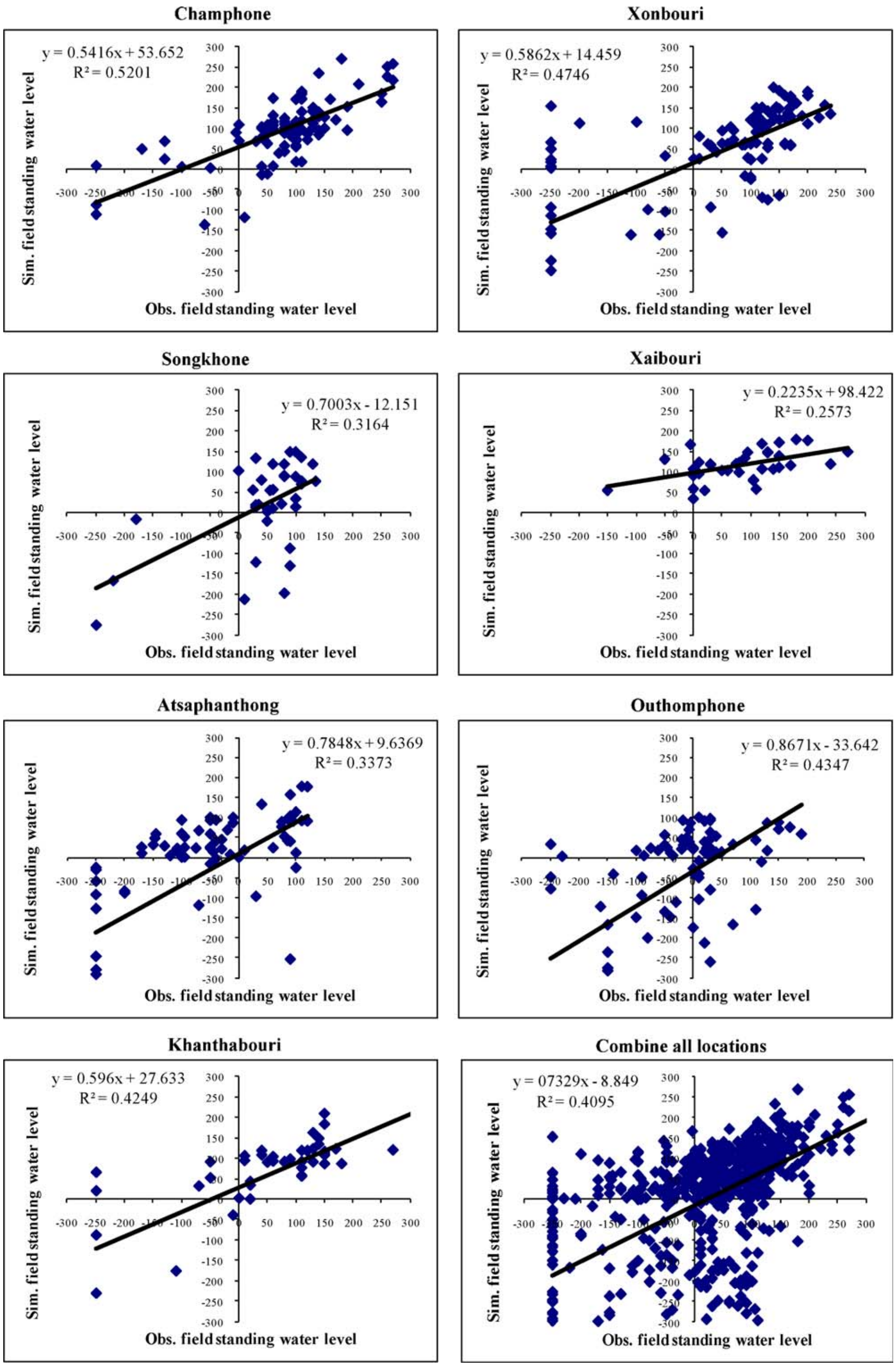

Fig. 3. The relationship between observed and simulated field standing water levels for middle toposequence for 7 districts and all districts combined in Savannakhet province, Laos.

above soil surface, and the mean water level at the bottom position exceeded 50 mm above soil surface.

4. Simulation exercises

4.1. Estimation of the separate effects of rainfall and soil clay content on LGP

A comparison of simulated LGP results for rice fields in two locations with soils of similar clay content and different rainfall in the south (a high rainfall area) and in the northwest (a low rainfall area) showed that, as a result of differences in rainfall the duration of the LGP varied by up to 4 weeks, with a 1 week difference for the start of growing period (SGP) and a 3 week difference for the end of growing period (EGP, Fig. 4a). On the other hand, the simulated LGP for areas based on soils with contrasting clay contents but with similar rainfall patterns showed similar SGP in week 20, but large differences in the end of growing season between the sandy (week 41) and clayey (week 45) soil sites (Fig. 4b).

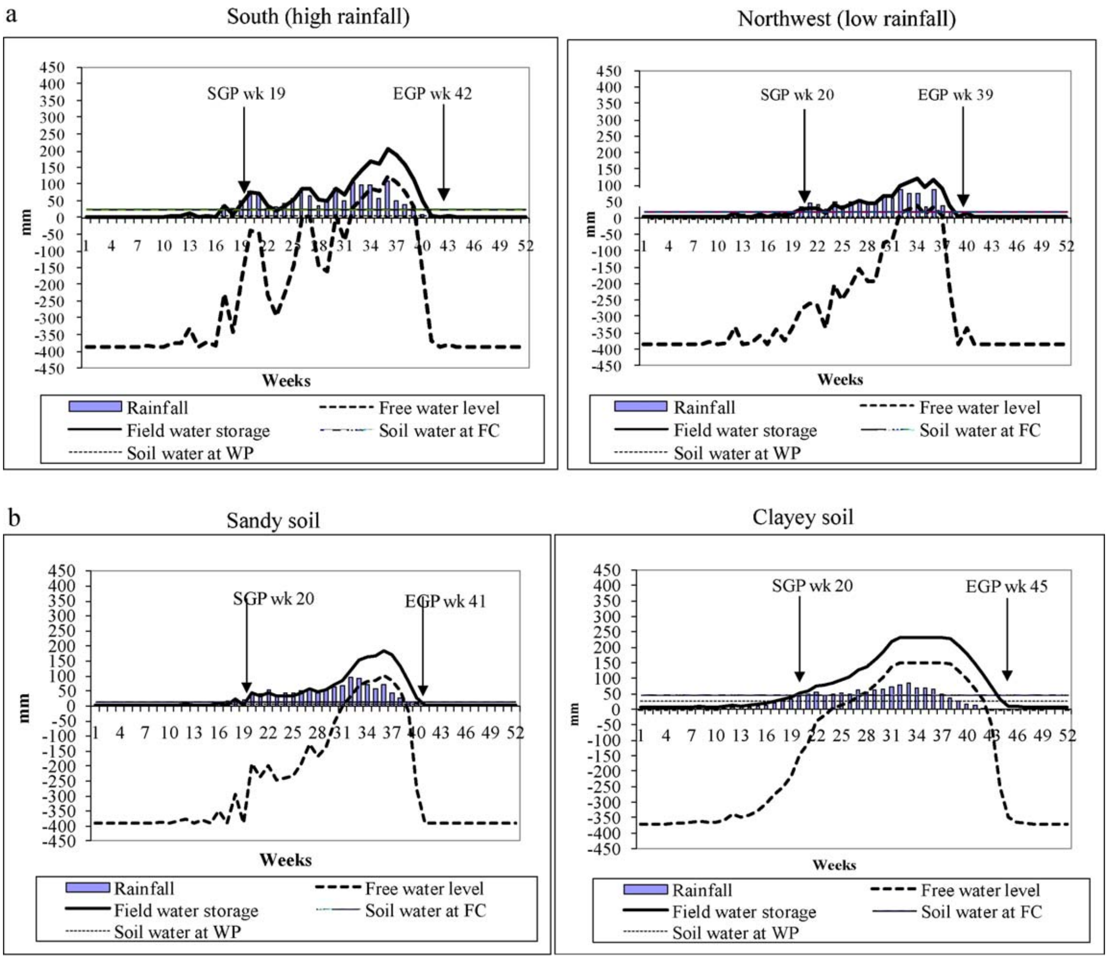

Fig. 4. Comparisons of field water stored between locations with: (a) similar in soil type but contrasting in rainfall pattern; and (b) similar rainfall pattern but different soil clay content.

4.2. Estimation of LGP probability and stress development during growing season

The simulated results (Table 4) indicate that Thapho (higher clay soil) has a longer mean LGP of around 27 weeks, with a LGP range of 23–31 weeks, over the 20 year period. In Seno (lower clay soil) the shorter growing period (LGP of 22 weeks) was associated with mean SGP and EGP values of week 22 and week 42, respectively. The difference in year-to-year LGP variation between the two locations reflects differences in soil clay content and rainfall distribution pattern. For example, the shortest LGP (11 weeks) at Seno site in the year 1995 was associated with a delay in the onset of wet-season and low rainfall for that year. The seasonal variation in field water availability also showed that wet-season rice planted at Seno would encounter drought stress more frequently than at the Thapho site. For example, in Seno the chance of early season drought between weeks 18 and 29 (between May and July) is 11 years in 20 years, mid-season drought between weeks 30 and 39 (between August and September) 7 years in 20 years, late season drought between weeks 40 and 44 (October–early November) 6 years in 20 years. For Thapho, the probability of occurrence of early, mid and late season drought is 3, 0 and 4 years in 20 years, respectively.

The 50% cumulative probability level of LGP for wet-season lowland rice at the Thapho site (higher clay soil) was about 26 weeks, with the SGP and EGP being in weeks 19 (mid May) and 45 (mid November), respectively (Fig. 5a). In the case of Seno (lower clay soil, Fig. 5b), the median growing season started one week later (in week 20) and ended three weeks earlier (in week 41), with the LGP being about 22 weeks (4 weeks shorter than for Thapho). The slope of the cumulative probability function of the weekly start and duration of growing period, was less steep for rice fields in Seno than Thapo. The slope of SGP was also less than for EGP at both locations, while the slope of EGP was similar between the two locations. These results indicate that year-to-year variation in SGP and LGP would be larger in low clay soils than in high clay soils.

Fig. 6 shows the relationship between SGP and rainfall in April, and also between EGP and rainfall in October, for the sandy soil texture, using Savannakhet meteorological station climate data set from the period of 1985–2004. The relationship between the SGP and monthly rainfall in April showed a significant negative correlation (Fig. 6a; $r = -0.59^{**}$, $n = 20$), and also SGP was significantly correlated with rainfall in May ($r = -0.51^{*}$, $n = 20$). A positive correlation was found between the EGP and monthly rainfall in October

Table 3
The comparison of simulated and observed standing water levels at three toposequence positions of rice fields in Savannakhet province, Laos.

Total 44 sites	Top position[a]	Middle position[a]	Bottom position[a]
Obs. mean water level (mm)	−27.9	26.7	58.8
Sim. mean water level (mm)	−13.2	30.4	51.5
Bias	14.8	3.8	−7.3
RMSE (mm)	128.3	102.9	112.8
r^2	0.37	0.41	0.32
IA	0.55	0.72	0.64

Table 4
Simulated start (SGP), end (EGP) and the length of growing period (LGP), and the timing (week of the year) of the occurrence of water stress for wet-season rice crops planted at the Thapho site (a high clay content) and Seno site (a low clay content) of Savannakhet province, Laos.

Year	Thapho [a high clay site]					Seno [a low clay site]				
	Annual rainfall	Growing period[a]			Water stress[b]	Annual rainfall	Growing period[a]			Water stress[b]
		SGP	EGP	LGP			SGP	EGP	LGP	
1985	1435	17	45	29	20	1252	24	41	18	
1986	1383	16	45	30	44	1502	20	42	23	
1987	1254	22	45	24		1246	25	43	19	41
1988	1134	17	45	29	44	1484	19	43	25	24,25,39,42
1989	1498	21	46	26		1711	27	46	20	
1990	1714	19	48	30		1895	17	44	28	21,43
1991	1539	25	47	23		1456	23	44	22	31
1992	1376	20	43	24		1256	19	42	24	29,31
1993	1125	19	43	25		1249	19	42	24	24,26
1994	1603	19	45	27		1370	19	42	24	23,26,27
1995	1351	19	44	26		894	29	39	11	32,33,38,39
1996	1940	16	45	30		1313	29	45	17	44
1997	1335	21	44	24		1046	24	39	16	27,39
1998	1070	19	42	24	29,41	921	26	40	15	29,39
1999	1600	16	44	29		1243	18	39	22	26,39
2000	1594	16	46	31		1490	16	43	28	18,26
2001	1920	17	45	29		1974	20	42	23	
2002	1982	19	44	26		1696	19	43	25	42
2003	1199	20	43	24	24,28,29,42	1625	21	43	23	28,42
2004	1650	19	44	26		1656	19	41	23	22
Mean	1485	19	45	27		1413	22	42	22	

Note: Numbers, e.g. 23, 34 shown in growing period and water stress columns indicate weeks of the year, except for those shown for LGP (duration).
[a] SGP is start of growing period (start at week); EGP is end of growing period (end at week); LGP is the length of growing period (number of weeks).
[b] Early season drought (May–July; weeks 18–29); Mid season drought (August–September; week 30–39); Late season drought (October–early November; weeks 40–44).

(Fig. 6b; $r = 0.61^{**}$, $n = 20$), but there was no significant correlation for November rainfall ($r = 0.16^{ns}$, $n = 20$). The statistical analysis suggests that the yearly variation in the SGP and EGP are attributed to rainfall occurring at the beginning and end of the growing season (April–May and October). For example, as shown in Fig. 6, in 1996 the growing season started early, in week 16, as a result of a large amount of rainfall in April (286 mm), while in 1991 the SGP was delayed to week 25 as a result of very low rainfall in the early part of wet-season (5 mm in April). In addition, the variation in EGP with the October rainfall was smaller than the variation in SGP with the April rainfall. Thus, for a given site, LGP is affected by early rainfall occurring in April–May and late rainfall in October, but the former had a larger effect.

4.3. Interaction between rainfall patterns and soil texture types

The results shows that the CL soil texture was associated with the longest growing period, with a mean LGP of 28 weeks and a LGP range of 23–32 weeks over the 20 years (Table 5). In contrast, for the SA soil texture, the growing period was shorter (a mean of 25 weeks and a range of 22–30 weeks) than other soils with higher clay content. While the mean LGP did not differ among the

Table 5
Simulated effects of different soil texture types found in Savannakhet Province on the length of growing period for year 1985–2004 with rainfall from the Savannakhet Meteorological Station, Laos.

Year	Rainfall (mm)			Sand (SA)			Loamy sand (LS)			Sandy loam (SL)			Loam (L)			Clay loam (CL)		
	Annual	April	October	SGP (week)	EGP (week)	LGP (week)	SGP (week)	EGP (week)	LGP (week)	SGP (week)	EGP (week)	LGP (week)	SGP (week)	EGP (week)	LGP (week)	SGP (week)	EGP (week)	LGP (week)
1985	1435	70	129	17	44	28	17	45	29	22	46	25	22	47	26	22	48	27
1986	1383	123	107	16	42	27	16	45	30	18	45	28	18	47	30	18	47	30
1987	1254	41	64	22	44	23	22	45	24	22	45	24	24	46	23	24	47	24
1988	1134	73	190	17	44	28	19	45	27	19	45	27	19	46	28	19	47	29
1989	1498	113	149	21	44	24	21	46	26	21	46	26	21	48	28	21	48	28
1990	1714	14	158	19	46	28	19	47	29	19	48	30	19	49	31	19	49	31
1991	1539	5	169	25	46	22	25	47	23	25	47	23	25	48	24	25	48	24
1992	1376	69	61	20	42	23	20	43	24	20	44	25	20	45	26	20	45	26
1993	1125	26	2	19	40	22	19	43	25	19	43	25	19	44	26	19	44	26
1994	1603	49	60	19	44	26	19	45	27	19	46	28	20	47	28	20	47	28
1995	1351	40	88	19	43	25	19	44	26	19	44	26	22	45	24	22	46	25
1996	1940	286	42	16	45	30	16	45	30	16	45	30	16	46	31	16	46	31
1997	1335	75	91	21	43	23	21	44	24	21	44	24	24	45	22	24	46	23
1998	1070	25	26	19	40	22	20	42	23	20	42	23	20	43	24	20	45	26
1999	1600	173	42	16	42	27	16	44	29	16	45	30	16	46	31	16	46	31
2000	1594	258	29	16	44	29	16	45	30	16	46	31	16	47	32	16	47	32
2001	1920	54	86	17	44	28	17	45	29	17	45	29	17	47	31	17	47	31
2002	1982	23	27	19	43	25	19	44	26	19	44	26	19	45	27	19	45	27
2003	1199	35	5	19	42	24	20	43	24	20	43	24	20	44	25	20	44	25
2004	1650	44	0	19	43	25	19	44	26	19	44	26	20	45	26	20	45	26
Mean	1485	80	76	19	43	25	19	45	27	19	45	27	20	46	27	20	47	28

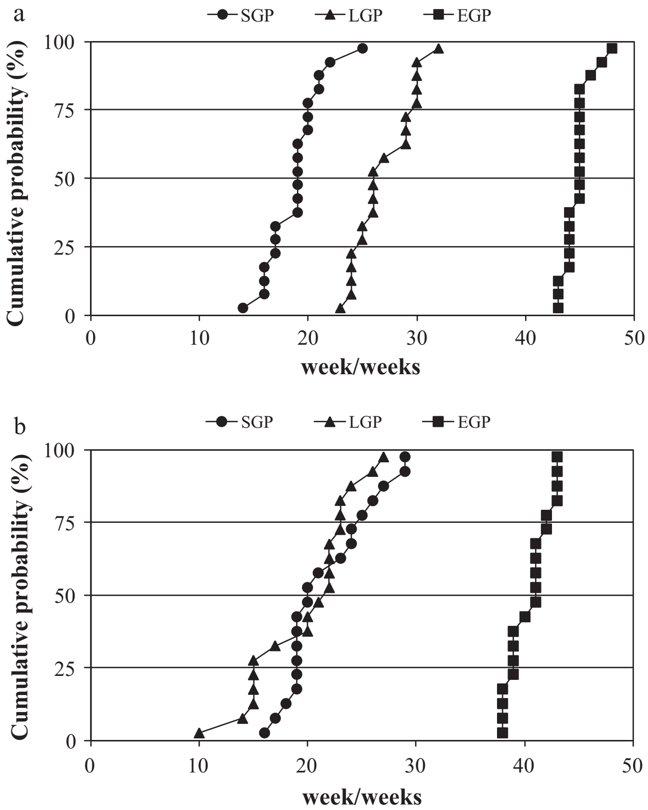

Fig. 5. Cumulative probability (%) of the occurrence for the start (SGP), end (EGP), and LGP (weeks) for: (a) Thapho—a high clay content site and, (b) Seno—a low clay content site, in Savannakhet province, Loas, using long-term climate data records (1985–2004).

LS, SL and L (there was an average LGP of 27 weeks), there were large annual variations (between 7 and 10 weeks) in the LGP and for the SGP and EGP, of 9 and 5–6 weeks, respectively, depending on soil texture type. These differences in SGP and EGP can be attributed to a number of factors, such as intensity and frequency of rainfall occurring in the early (e.g. April–May) and late (e.g. October–November) part of the growing season. For example, in both 1996 and 2000, due to heavy rainfall in April (286 mm in 1996 and 258 mm in 2000), the growing season started early, in week 16 for all soil texture types. However, in those years with low and uneven rainfall distribution early in the season (in 1987, 1989 and 1991) the SGP was delayed. Although fairly high rainfall was recorded in both April and May in 1989 (113 mm and 149 mm, respectively) the SGP was delayed until week 21. This reflected the discontinuous nature of rainfall pattern in that year, with initial heavy falls followed by little rain until the end of April.

5. Discussion

The simulation results indicate that both rainfall and soil type have a significant effect on the duration of the growing period in rainfed lowland rice. Differences in LGP between the two locations (i.e. south and northwest where soils had similar clay content) are attributed to variation in rainfall (Fig. 4a). Less water being stored in the fields during the growing season and shorter LGP, reflects a decline in rainfall from south to northwest of the province (Inthavong, 2009). The variability in LGP also clearly showed that clayey soils have a longer LGP than sandy soils (Fig. 4b). The positive effect of soil clay content on LGP was expected, given that soils with high clay content generally have higher water holding capacity and slower downward water movement, relative to low clay content soils. Kirchhof et al. (2000) suggested that the amount of water that can be stored in the soil and also the capacity of the soil profile to accept water affect the growing period. Higher soil clay content results in higher residual water content at the end of rain period, thereby lengthening the duration of water availability in the field (Kam et al., 2000; Fukai et al., 2007). This is in contrast to sandy soils with high drainage and low water holding capacity, which contribute to a shorter growing period. As shown in Table 5, the mean SGP (averaged over 20 years) did not significantly differ varying between week 19 and week 20 among soil texture types contrasting in clay content. However, EGP was highly variable, with mean values ranging from week 43 to 47 weeks. This suggests that the EGP is more affected by soil type than is SGP. This can be explained by soils with a higher clay content generally having a low downward water loss, and thereby able to retain more water at the end of the growing season. Fine textured soils therefore have a relatively longer LGP when compared with coarse soils.

However, when considering year-to-year variation in LGP, it is variation in SGP that is more important (Table 4, Fig. 5). It appears that uncertainty in the onset of wet-season is an important factor affecting the SGP and LGP. Oladipo and Kyari (1993) report similar finding that the LGP is more sensitive to the rainfall at beginning of the growing season than to the cessation of rainfall at the end of the season, for investigations in the onset, cessation and LGP in Northern Nigeria. In the present study, the assessment of LGP based on cumulative frequency analysis of long-term data has provided the probability of the occurrence of LGP, which can then be represented as a reliable LGP estimate for planting rainfed lowland rice in Savannakhet province. For farmers who have rather small fields [average of 2.2 ha, with approximately 90% of households having between 0.1 and 4.0 ha (Manivong and Douangsavanh, 2007)], variability in soil and rainfall at the farm level is rather small, but year-to-year variability at the beginning of year has important implications for

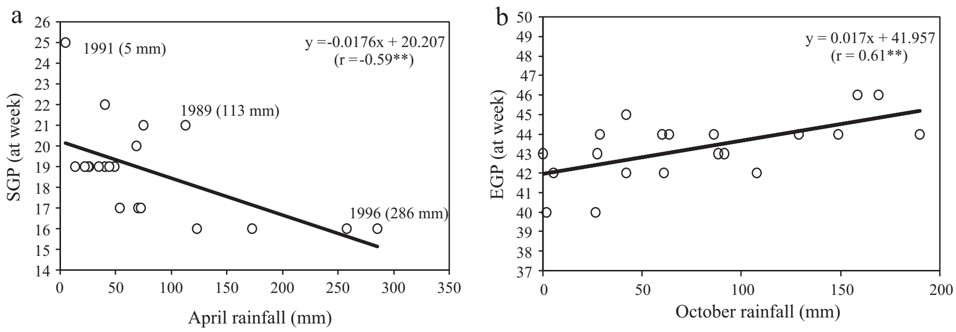

Fig. 6. Relationship (a) between the start of growing period (SGP) and April rainfall and (b) between the end of growing period (EGP) and October rainfall, for sandy texture (SA) soils. The years 1996 and 1991 were chosen to provide a contrast of high and low rainfall in the early and late parts of the growing season.

their rice cropping cycle, particularly with the increased adoption of photoperiod insensitive cultivars with a fixed growth duration.

Large downward water loss (*D*) can result in low water use efficiency (Watanabe, 1992), with associated nutrient leaching. A reduction in *D*, therefore, not only lengthens the duration of water availability, but can also improve nutrient use efficiency in rice fields (Ponnamperuma, 1972; Patrick and Reddy, 1978). Soil compaction and puddling are the most efficient methods for reducing *D* in irrigated and rainfed lowland rice fields, especially in sandy, coarse-textured soils (Ghildyal, 1969; Patel and Singh, 1986; Sharma et al., 1995). Sharma et al. (1995) have shown that *D* can be decreased by up to 70% as a result of puddling a fine-textured soil. They also reported that compaction can increase the total number of days with surface water ponding from 44 days in dry tillage conditions, to 68 days in response to farmer's puddling practices. While *D* is greatly affected by clay content alone ($r = 0.67$) in the present study, there are other soil characters that can affect *D*, such as degree of plough pan as shown above and also the mineralogy of the clays and dispersiveness of clays. The equation used in the model can provide a good first estimation of the spatial differentiation of *D* that can help in characterization of field water availability with particular focus on drought risk for rainfed lowland rice. Further improvement can be made when the importance of some of these characters is quantified and data become available.

Inadequate water during a growing season usually reflects a year with low rainfall in early part of season, as shown in Table 5. For example, in 1991 when the April rainfall was just 5 mm, the growing season started late (week 25) for all soil texture types, with resulting short LGPs (22, 23, 23, 24 and 24 weeks for soil types SA, LS, SL, L, and CL, respectively). It would be anticipated that the resulting grain yields for that year would be considerably lower than average, due to delays in transplanting and as a result of the impact of dry conditions around flowering time. Similar findings have also been reported by Jearakongman et al. (1995) and Jongdee et al. (2006) for a similar growing environment in Northeast Thailand, in which they found that in years with low rainfall when standing water in rice fields disappeared about flowering time, grain yield could be reduced by up to 70%. The results of the simulation studies reported in this study indicate that further analysis is required of the impact of frequency and severity of drought stress at different stages of crop growth for the different soils types.

For the two sites with long-term rainfall data are considered, the simulated field water availability shows rice planting in Seno with a lower clay content soil encountered dry conditions around transplanting (June–July) and towards the end of the growing season (October–November) more frequently than the Thapho site, with a higher clay content (Table 4). The results confirm that greater growing season stress is likely to occur in areas with a short LGP, as the short LGP was strongly associated with low clay content soils. Drought can develop at any time during the growing season, particularly in rice fields in the upper part of the toposequence, where soils are light in texture and where water is more readily lost (Jongdee et al., 2006). In areas with low clay content soils, quick maturing, drought tolerant varieties should be planted immediately after the beginning of wet-season to avoid late season drought (Fukai and Cooper, 1995). Planting photoperiod insensitive varieties too early, on the other hand, may result in the crop maturing very early, resulting in harvesting and post-harvest processing difficulties associated with late wet-seasons rains (Romyen et al., 1998).

The soil water balance model used in the study was developed with the aim of quantifying field water availability for rainfed lowland rice. While the model has provided satisfactory prediction of water conditions in rice fields in the middle part of toposequence, the prediction was poorer for upper and lower parts of the toposequence. This mainly reflects the fact that the model does not have the capability of estimating lateral water movement, which is highly dynamic and spatially variable within a landscape (Fukai et al., 2000; Kam et al., 2000). In fact, the concept of lateral water movement was also included in the water balance equation for this study, but the prediction of this lateral seepage is very complicated, as the field is subjected to various factors such as soil physical and hydraulic properties, hydrologic environment and also landscape of the fields. Because of the paucity of data for these soil physical and environmental attributes, the prediction of this lateral flow/seepage loss was done through a simple mathematical modelling in which lateral flow rate is included as a part of deep percolation rate; that is, when downward water loss (*D*) from the top soil layer is greater than deep percolation loss (DP) under subsoil layer, and water stored in the subsoil layer exceeded subsoil water storage conditions (assuming there is no water loss through deep percolation under this condition), the difference between *D* and DP is assumed as the lateral seepage through the bund.

There is no measurement of lateral flow/seepage loss to test the prediction of this study and also there is no toposequence position as input to the model, and hence there is no lateral water flow rate estimated for any toposequence position. Further, considering that the model was developed as one dimensional water balance (upward and downward), it was used to map spatial variation in field water availability at regional scale rather than at toposequence scale. Moreover, although the topography of paddy fields is mixed with different toposequence positions, the cross flow (lateral seepage) is varied over short distance, i.e. lateral water movement generally increases in fields higher in the toposequence while fields in lower position have low lateral seepages. These are not captured at the large scale or resolution covering the entire province, so the lateral flow or seepage loss through the bunds was neglected in quantifying field water storage for rainfed lowland rice in this study. If the toposequence position is included in relation to lateral flow in the model, the model could improve its capacity to predict water availability at different toposequence positions. Currently, there is overestimation/underestimation of water availability at different toposequence positions with no specific value assigned to the lateral flow. However, the water moves from top (loss) to bottom fields (gain), and the net effect of lateral flows within a whole mini-catchment would be small. The variation in water availability within a mini-catchment is underestimated without estimating lateral flow properly, but the mean water availability may be reasonably well estimated. Thus the overall effect on water availability in the mini-catchment may be rather small.

6. Conclusion

This study reports on the newly developed soil water balance model for making estimates of stored field water, for defining the LGP and water stress development during growth for rainfed lowland rice crops. The model generally produced reasonable results in estimating field standing water levels, which were supported by field observation data obtained for a wide range of soils and rainfall patterns across Savannakhet province. The analysis of the effect of soil texture and rainfall on LGP showed that monthly rainfall and the clay content of soils are crucial factors in affecting year-to-year variation in the SGP and EGP. The variation in yearly SGP largely reflects the quantity of rainfall received in the early part of the wet-season (April–May), while the EGP strongly reflects the soil clay content. The results also clearly indicate that soils with a higher clay content had slower downward water movement, thereby increasing the probability of there being standing water above the soil surface that can, in turn, lengthen the LGP at the end of the growing season. The model, therefore, could be employed to characterize the spatial pattern of paddy water availability for the rainfed lowland rice ecosystems. It can help in the determination of appropriate crop and soil management strategies capable of bringing about a combination of improved and more stable yield across years (Fukai and Cooper, 1995; Kam et al., 2000). The model combines soil and climate information which, with GIS based links, can provide the spatial pattern of field water availability on a provincial or regional scale. The model can be used to characterize and map the LGP for rainfed lowland rice, and it has the potential for helping identify areas where drought is likely to occur, thereby allowing more precise geographical targeting of different parts of the province with improved varieties with drought tolerance characteristics and cultural management to reduce the impact of drought.

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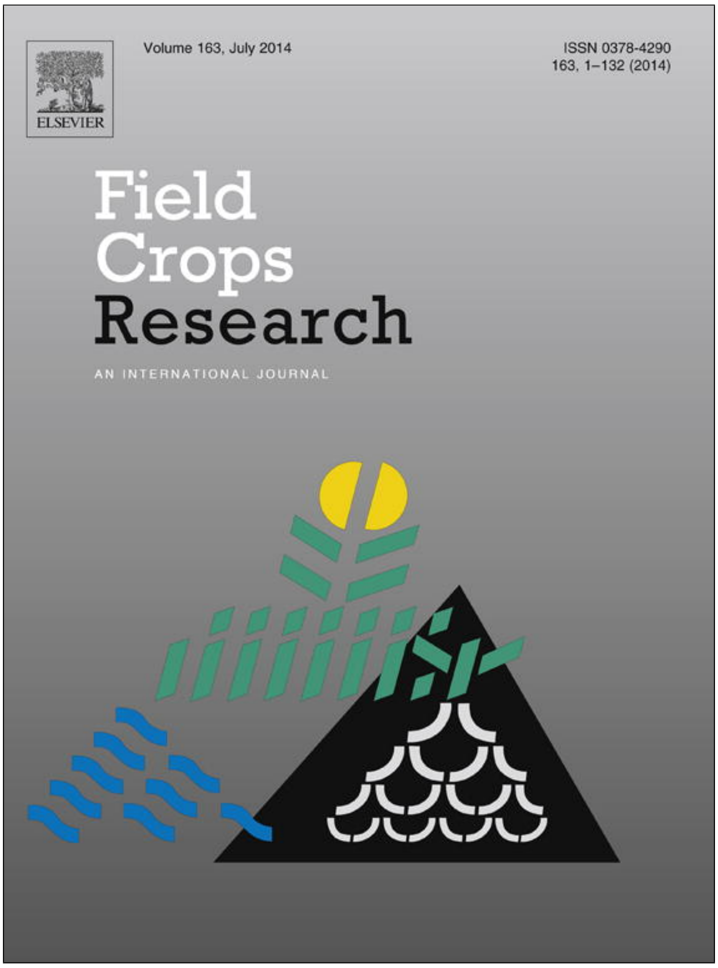
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Estimation of separate effects of water and nutrient limitation for rainfed lowland rice within a province in the Mekong region

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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 t ha^{-1}). The amount of fertilizer needed to produce the target yield [fertilizer requirement (FR, kg ha^{-1})] can be calculated by subtracting the amount of nutrient available in the soil [inherent nutrient supply (N_{ind}, kg ha^{-1})] from the amount of nutrient needed to produce the yield target [nutrient uptake required for the yield target (NU_{target}, kg ha^{-1})], and then divided by the recovery efficiency of applied nutrient (RE, kg fertilizer nutrient taken up per kg applied):

$$FR = \frac{NU_{target} - N_{ind}}{RE} \quad (1)$$

The required nutrient uptake is provided by Witt et al. (1999); 15 kg N ha^{-1}, 2.6 kg P ha^{-1} and 15 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 (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 under rainfed lowland conditions across two provinces (Savannakhet and Champassack) in Southern Laos, during the period 2000–2002 (Tsubo et al., 2006). Additional rice data collected from rice fields in 13 districts of Savannakhet, representing different growing environments and covering a wide range of soils, agronomic practices and climatic condition for the 2007 and 2008 wet season (Inthavong et al., 2011a), were also included in the dataset to define the flowering date for each genotype group. The time required to reach flowering ranged from between 87 and 105, 98 and 117, and 104 and 138 days, for early, medium, and late maturity groups, respectively. Once the flowering date was determined and matched with the corresponding WL_{REL}, the spatial variation in yield reduction (YR) was estimated from the simple equation of Ouk et al. (2006), and the yield loss percentage was then multiplied with the yield obtained from the nutrient model to provide yield under both nutrient and water limiting conditions. The equation developed by Ouk et al. (2006) under Cambodian rainfed lowland conditions was:

$$YR = -1.68 \quad WL_{REL} \tag{2}$$

where YR is yield reduction (%), and WL_{REL} is the relative water level (cm). This model uses free water level (FWL) between the well-watered and water stressed treatments around flowering (3 weeks before and after flowering date), as an index of the severity of the water deficit to describe yield reduction. WL_{REL} is zero when FWL is equal to or higher than the soil surface, while WL_{REL} is 0 – FWL when FWL is lower than the soil surface. This relationship shown in equation 2 would include not only the direct effect of plant water deficit but also the indirect effect of nutrient deficiency caused by anaerobic soil conditions. Although the indirect effect through nutrient deficiency may be different if soil pH and other chemical properties differ between various rainfed lowland rice environments in Cambodia and Laos, the direct effect of water stress would be similar between the two countries. Generally the direct effect of water deficit would be more important under severe drought stress conditions (Fukai and Ouk, 2012; Pantuwan et al., 2002).

2.3. Model inputs

Standard inputs of the combined model are described here. Soil information was obtained from the soil database (SSLCC, 1996), where soil physical and chemical analysis data were available for calculating volumetric soil moisture content and inherent soil nutrient supply for Laos. Climatic data recorded for the period 1985–2007 for a total of 62-point locations; 43 locations within Laos, and 19 meteorological stations in neighboring Northeast Thailand were used to generate gridded surfaces of long term median weekly rainfall and potential evapotranspiration which were used as inputs into the model

The model was run for high yielding, medium maturing, non-photoperiod sensitive variety Thaddokkham-1 (TDK1). The mean HI of 0.45 obtained under rainfed lowland conditions over two years (1996–1997) for Savannakhet province, Laos (Inthapanya et al., 2000a) was used as an input. The 1st June sowing date was selected as a common practice for rice farmers in this province. A summary of model input requirements for simulation runs is given in Table 1.

2.4. Datasets for model validation

The model was validated using three data sets. The first set uses farmers' survey results from the wet season, while the second set uses results of a fertilizer experiment conducted under irrigation in the dry season. The third set of data was from the results of published nutrient omission trials from central and southern Laos (Linquist and Sengxua, 2001). The first and third data sets are from the wet season and the model was tested for both water and nutrient limiting conditions, while the second set was used only to test the nutrient model under non-limiting water conditions.

Table 1
Model input data requirement.

Crop growing cycle (days)
Cultivar
Fertilizer application rate
Harvest index
Organic carbon, total P, exchangeable K and pH
Sowing date
Volumetric soil moisture content, i.e. saturation, field capacity, wilting point and air dry condition
Weekly potential evapotranspiration
Weekly rainfall

For the first data set, rice yields from 53 farmers' fields in 2007 and 48 in 2008 in Savannakhet province, Laos, were estimated using the combined model (Fig. 1). Using geographic information system (GIS) software, the soil information for each farm was extracted from the interpolated gridded soil surface map generated from 339 soil profile samples (SSLCC, 1996) predominantly taken from agricultural land. Inherent soil nutrient supply was calculated following equations of Janssen et al. (1990) and Mulder (2000), while volumetric soil moisture contents at each threshold of wilting point, field capacity and saturation were calculated using the method of Saxton and Rawls (2006) and used as soil information inputs for each site. The model was run using farm management practice (e.g. rice cultivar, sowing date, fertilizer application rate, standing water level at transplanting time) obtained from field surveys conducted in 2007 and 2008 (Inthavong et al., 2011a). The farmers were interviewed for information on rice grain production, harvest area and the farm management practices utilized. The yield was then estimated by dividing the production by the harvested area. The 2007 and 2008 gridded rainfall surfaces generated from 2 meteorological and 11 hydrological stations were employed as the weather inputs. The model performance was evaluated with Bias (average yield differences), coefficient of correlation (r) and the Index of Agreement (IA; Willmott, 1981).

The second data set comes from a 2011 dry season experiment in which 8 locations were selected from 3 Provinces (Savannakhet, Vientiane and Champassak) for their contrast in soil fertility attributes (organic matter, extractable P and K with known pH level) under two fertilizer rates; the rate of farmer practices and the rate estimated from the combined model to achieve target grain yield of up to 5000 kg ha^{-1}. At all locations, variety TDK1 was broadcast, and the crop was grown under irrigated conditions.

3. Results

3.1. Model validation

When the simulated grain yield with both nutrient and water limitations were compared with the actual yields, the model overestimated grain yield for the early genotype group by 650 kg ha^{-1} for 2007. The simulated grain yields for the medium and late genotype groups, however, showed a close relationship with the actual yields (Table 2). The overall estimates were regarded as being satisfactory, with $r = 0.54$ ($n = 53$, $p < 0.01$) and IA = 0.69. Similarly, the level of agreement between simulated and observed grain yield for 2008 was satisfactory, with an overall mean r of 0.54 ($p < 0.01$, $n = 48$), a Bias (average yield differences) of 151 kg ha^{-1} and IA of 0.67. The model provided a good estimate of grain yield for the early genotype group, with high values of r and IA [0.75 ($p < 0.01$) and 0.78, respectively], while a satisfactory result was obtained for the medium group, with an acceptance r value of 0.49 ($p < 0.01$) and IA of 0.62. There was no yield analysis for late genotype group, due

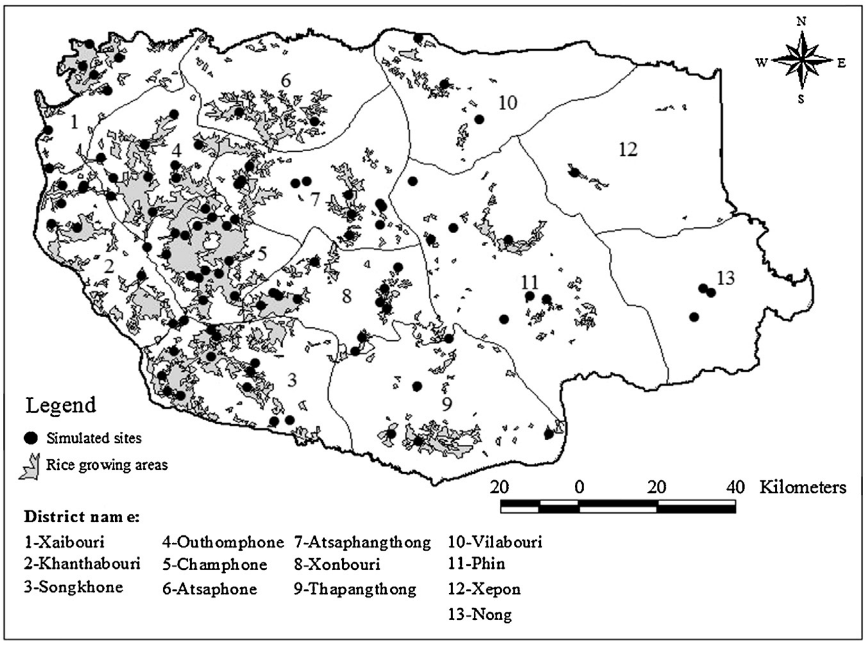

Fig. 1. Locations used for simulated rice yield under soil nutrient and water stress conditions across Savannakhet province, Laos.

Table 2
Model validation for grain yield for early, medium, and late genotype groups over two rice cropping seasons 2007 and 2008 in Savannakhet province, Laos.

Statistics	2007 season				2008 season		
	Early	Medium	Late	All	Early	Medium	All
Number of samples	10	36	7	53	9	39	48
Bias (kg ha^{-1})	650	92	169	208	198	246	151
Coefficient of correlation (r)	0.59 ($p > 0.05$)	0.58 ($p < 0.01$)	0.57 ($p > 0.05$)	0.54 ($p < 0.01$)	0.75 ($p < 0.05$)	0.49 ($p < 0.01$)	0.54 ($p < 0.01$)
Index of Agreement (IA)	0.48	0.73	0.97	0.69	0.78	0.62	0.67

Note: There was no yield analysis for late maturity variety in 2008 due to only a few farms planted this maturity type.

to the small number of farms that used late varieties. When the two year results are combined, the correlation coefficient was 0.54 ($p < 0.01$) with $n = 101$.

For the validation of nutrient-limited yield without water limitation in the dry season, eight farmers applied fertilizer to dry season irrigated rice crops both under their own farm practice and that required (estimated) to achieve a target yield of 5000 kg ha^{-1}. The farm practice of fertilizer management, which varied among the 8 farms and could not be accurately quantified, produced yield that varied from 2300 to 5500 kg ha^{-1} (Table 3). The bottom row in Table 3 was the estimated amount of N–P_2O_5–K_2O kg ha^{-1} that was required to achieve a target yield of 5000 kg ha^{-1}; it varied from 84 to 121 kg N ha^{-1}, 52 to 63 kg P_2O_5 ha^{-1} and 0 to 39 kg K_2O ha^{-1}. The yield results have indicated that 3 out of 8 locations produced yield below 4000 kg ha^{-1}, but the other locations produced yield close to 5000 kg ha^{-1} with 3 locations exceeding the target yield. The low yielding crops had rather limited response to fertilizer and it is likely that factors other than NPK were involved. A weed problem was observed in these three farms (Table 3), and one also had a problem with irrigation. It should be pointed out that P fertilizer rate was high in all locations for the 'target yield' treatment (mean 60 kg P_2O_5 ha^{-1}), but this amount was probably not required as it was likely that the requirement of P was overestimated by the model when soil pH was rather low. The effect of low pH may not be large in lowland conditions with standing water throughout the growing period, as was the case in these experiments.

The simulation results of the effect of nutrient omission across the 53 farms were compared with published nutrient omission trial results (Linquist and Sengxua, 2001) conducted in rainfed lowland rice in central and southern Laos (Table 4). Table 4 shows the simulated yield level of 2932 kg ha^{-1} when the standard N–P–K rate of 60–13–16 kg ha^{-1} was applied, but the yield level would be 35% lower when N was omitted and 46% lower without any fertilizer application. Similar results were obtained experimentally with the corresponding yield of 3300 kg ha^{-1} and yield reduction of 27 and 39% respectively. Simulation results indicated a lower effect of P omission and little effect of K omission; these are in general agreement with Linquist and Sengxua (2001) who reported that the strongest effect was observed with N omission, followed by P omission and limited effect of K omission for central and southern Laos.

Simulated yield response (Table 4c) was largest (84% increase) when fertilizer was increased from zero to standard rate (60 N–13 P–16 K) after which the yield response was less, and additional 33% increase was estimated when the fertilizer rate was doubled, and further 19% increase when the fertilizer rate was tripled (180 N–39 P–48 K kg ha^{-1}). From the results of very high fertilizer input (6 times the standard rate), yield level of close to 6000 kg ha^{-1} was achieved and assumed to be yield when nutrients were unlimited.

3.2. Spatial variation on simulated yield under inherent soil nutrient supply and under recommended fertilizer rate application

Fig. 2 shows the spatial yield variation under inherent nutrient supply, without water stress across the province. The yield under different inherent nutrient supplies ranged from less than 1000 to

Table 3
Rice yield (kg ha^{-1}) at two fertilizer rates ($N–P_2O_5–K_2O$ kg ha^{-1}), farmer practice and estimated rate required to target grain yield of 5000 kg ha^{-1}, at eight locations [Phonhong (PH), Tulakhom (TK), Champhone (CP), Sakeun (SK), Beungxe (BX), Donekhor (DK), Saphai (SP), Vatsay (VS)] across three provinces in Laos in 2010/11 dry season. The bottom rows show estimated fertilizer rates ($N–P_2O_5–K_2O$) required for the target yield of 5000 kg ha^{-1} and observed field conditions.

	Vientiane		Savannakhet			Champassak			Mean
	PH	TK	CP	SK	BX	DK	SP	VS	
Farmer practice yield	3067	3750	2260	5525	3023	4747	5437	3561	3921
Target yield	4417	4894	3057	5566	3607	5072	5509	3977	4512
Fertilizer rate	110-63-34	91-62-10	121-62-0	100-60-7	94-52-39	106-63-36	113-57-30	84-61-0	
Field issues			W		W	FYM	FYM	W, S	

W: weed problem; FYM: additional nutrient input of farm-yard manure; S: water stress.

Table 4
Comparison of grain yield (kg ha^{-1}) in nutrient omission trials (a) simulated in this study and (b) observed by Linquist and Sengxue (2001), and (c) simulated effect of fertilizer rate relative to standard 60N-13P-16 K kg ha^{-1} (multiplier of this rate from 0 to 6 times (0×, 1×, 2×, 3×, 4×, 5×, 6×) the standard rate).

(a) Simulated effect of nutrient omission from the standard fertilizer rate (60 N–13 P–16 K)							
Fertiliser rate (N–P–K)	60–13–16	0–13–16	60–0–16	60–13–0	0–0–0		
Grain yield	2932	1895	2248	2822	1595		
Yield reduction due to nutrient omission		35%	23%	4%	46%		
(b) Observed effect of N omission from the standard fertilizer rate (60 N–13 P–16 K)							
Fertiliser rate (N–P–K)	60–13–16	0–13–16			0–0–0		
Grain yield	3300	2400			2000		
Yield reduction due to N omission		27%			39%		
(c) Simulated effect of fertilizer rate							
Times the standard rate (60 N–13 P–16 K)	0×	1×	2×	3×	4×	5×	6×
Grain yield	1595	2932	3914	4672	5194	5543	5774
Yield increase over the previous rate		84%	33%	19%	11%	7%	4%

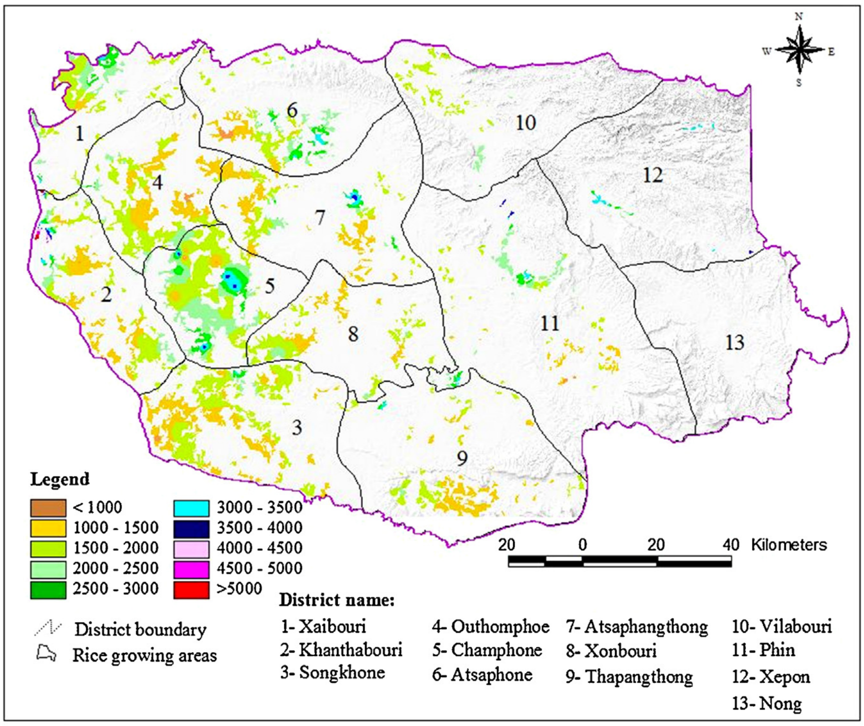

Fig. 2. The spatial variation of simulated rice yield under inherent soil nutrient supply for Savannakhet province, Laos.

Table 5
Examples of yield estimated from the combined model without any fertilizer inputs and also with no water stress, and soil information for rainfed lowland rice fields in Outhomphone, Songkhone, Atsaphone and Xepon districts of Savannakhet province, Laos.

	Outhomphone	Songkhone	Atsaphone	Xepon
Grain yield (kg ha^{-1})	913	1970	1457	3114
Organic carbon (g kg^{-1})	2.5	5.7	3.7	16.7
Total phosphorus (mg kg^{-1})	100	100	300	640
Exchangeable potassium (mmol kg^{-1})	0.5	1.8	0.7	0.9

greater than 5000 kg ha^{-1}; however, more than 75% of the total rice growing areas in the province were estimated to give yields between 1000 and 2000 kg ha^{-1}. The most productive areas that can potentially produce yield over 3500 kg ha^{-1} would account for just 1% of the total area used for rice cultivation in the province. Four representative fields from districts of Outhomphone (district number 4 in the figure), Songkhong (3), Atsaphone (6) and Xepon (12) were selected for comparing the model estimates of yield under a wide range of inherent soil fertility and climatic conditions across the province. The results (Table 5) show Xepon (12) gave the highest simulated yield (3114 kg ha^{-1}), following by Songkhone (3) (1970 kg ha^{-1}) and Atsaphone (6) (1457 kg ha^{-1}), whereas Outhomphone (4) gave the lowest yield of 913 kg ha^{-1}. The variability of yield among these sites corresponded with the variation in inherent soil fertility. The soil in the Xepon (12) area is more fertile than other sites, with higher organic carbon (16 g kg^{-1}), which was positively associated with the potential supply of N, and total P (640 mg kg^{-1}), while the Songkhone (3) site had higher exchangeable K content (1.8 mmol kg^{-1}) relative to other sites in this study (Table 5). These soil factors contributed to the highest uptake of N and P in Xepon (12) and K in Songkhone (3). Thus, higher yields are achieved in these sites, when compared with fields in Atsaphone (6) and Outhomphone (4).

Grain yield with a blanket recommendation of fertilizer application rate (i.e. currently 60 kg N ha^{-1}, 13 kg P ha^{-1} and 16 kg K ha^{-1} in Laos) was simulated for a total of 80 point locations in Savannakhet province. The average yield was 2800 kg ha^{-1}, ranging between 1400 and 5600 kg ha^{-1} (data not shown). The large variation was attributed to variation in inherent nutrient supply across the province.

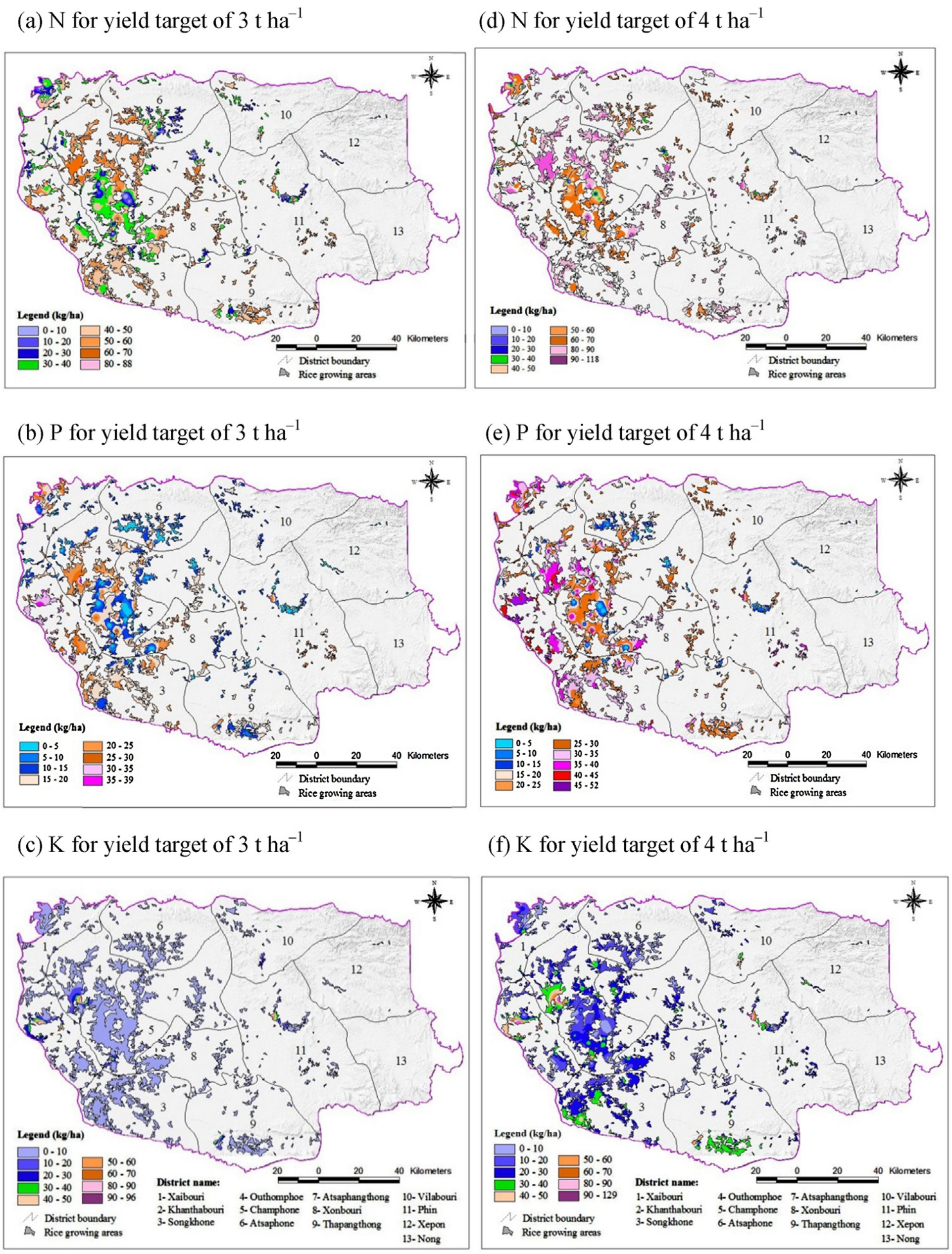

Fig. 3. Maps of nitrogen (N), phosphorus (P) and potassium (K) fertilizer requirement (kg ha^{-1}) for achieving yield targets of 3 t ha^{-1} and 4 t ha^{-1} in Savannakhet province, Laos.

Table 6
Simulated yield under inherent soil nutrient supply with no water limitation and with water limitation and yield reduction by water stress for 1st June 2007 sowing for 13 districts of Savannakhet province, Laos.

Zone	Number of locations	Yield under inherent soil nutrient supply (without water limitation) (kg ha^{-1})	Yield under inherent nutrient supply and under water limitation (kg ha^{-1})	Yield reduction due to water limitation (%)
Western zone				
Champhone (5)	11	1817	1568	14
Khanthabouli (2)	5	1657	1555	6
Outhomphone (4)	5	1498	958	36
Songkhone (3)	6	1818	1818	0
Thapangthong (9)	1	1936	1606	17
Xaibouri (1)	2	1875	1875	0
Whole zone	30	1767	1563	12
Central zone				
Atsphangthong (7)	5	1070	994	7
Atsphone (6)	3	1923	1894	2
Xonbouri (8)	6	1692	1612	5
Whole zone	14	1562	1500	4
Eastern zone				
Nong (13)	2	1561	1561	0
Phin (11)	3	1288	1288	0
Vilabouri (10)	2	2069	1582	24
Xepon (12)	2	2605	2605	0
Whole zone	9	1881	1759	6

3.3. Spatial variation on simulated fertilizer requirement for yield targets

Fig. 3a–f illustrate the maps of fertilizer N, P and K requirement for achieving yield targets of 3000 kg ha^{-1} and 4000 kg ha^{-1}, respectively. Corresponding to the spatial variability of inherent soil nutrient supplies, rate of N, P and K fertilizers between 20 and 70 kg ha^{-1}, 5 and 35 kg ha^{-1} and 0 and 10 kg ha^{-1}, respectively, are required for almost all paddy fields, to achieve the yield target of 3000 kg ha^{-1}. However, higher rates of N (exceeding 80 kg ha^{-1}) and P (exceeding 40 kg ha^{-1}) are required for yield targets of 4000 kg ha^{-1} in some fields in districts of Outhomphone (4) and Khanthabouri (2), respectively, where the organic matter and available P levels are the lowest. Even though the analysis of lowland rice soil data (0–200 mm) show that a large proportion of the paddy fields in Savannakhet province are classified as being in the moderate inherent K category (SSLCC, 1996; Linquist and Sengxua, 2001), supplementary K fertilizer, between 10 and 40 kg ha^{-1}, was needed to produce the yield targets in some fields.

3.4. Yield limitation by water stress under inherent soil nutrient supply

Yield reduction due to water stress was simulated under inherent soil nutrient supply. The simulated results for the 2007 wet season (Table 6) shows Outhomphone (4) district encountered severe water stress in response to late season drought which caused a maximum yield reduction of 36%, followed by Vilabouri (10), Thapangthong (9) and Champhone (5) districts for which yield loss varied from 14 to 24%. Water stress also would have occurred in rice fields in Atsaphangthong (7), Khanthabouri (2), Xonbouri (8), and Atsphone (6) districts, but the severity level in terms of yield loss was smaller (2 to 8%). The expected yields including the effect of water stress would have been reduced from 1498 to 958 kg ha^{-1} in Outhomphone (4) and from 2069 to 1582 kg ha^{-1} in Vilabouri (10). It was noted that severe drought stress would have extended over a large area of rice fields in the western part than in the central and eastern parts of the province, with the overall mean yield loss of 12%, 4% and 6%, respectively.

4. Discussion

4.1. Model performance

The overall results of the model performance on yield estimation were satisfactory. The simulated results matched reasonably well with yield data from the 101 farmers' fields collected in 2007 and 2008 wet seasons, and with the results of fertilizer requirement experiment conducted in dry season under no water limiting conditions. The simulated effect of fertilizer application also matched with the results of nutrient omission trials of Linquist and Sengxua (2001) where grain yield response to N, P and K omission was studied widely in central and southern Laos. Our simulated yields under the recommended fertilizer inputs for Savannakhet province were slightly lower than those reported by Linquist and Sengxua (2001), probably because of the lower soil fertility of rice fields of Savannakhet province compared to that of the whole central and southern parts of Laos.

The model used in this study was a combination of two published models, and the water balance model itself was validated earlier with measured soil water levels throughout the growing period at 48 farms in 2008 (Inthavong et al., 2011b). Similarly the nutrient model has been widely tested in tropical region of Asia by the authors Witt et al. (1999) and Witt and Dobermann (2002). However, because simulation models are simplified descriptions of complex field situations, there are always factors that may not be included but could affect crop performance and hence yield. In the current combined model of rainfed lowland rice, key factors that are not included in the model are toposequence position effect, subsoil constraints including soil compaction, nutrient toxicity effects as well as biotic constraints due to weeds, diseases and insect pests. Toposequence effect is a unique feature of the rainfed lowlands, and Tsubo et al. (2006) and Inthavong et al. (2011a) among others have found variation in water availability and yield across toposequence positions. Subsoil compaction is a common problem in rainfed lowland fields which may affect rice yield through the adverse effect of stagnant water and possible nutrient toxicity such as iron toxicity. The performance of the model would be improved if these factors are successfully incorporated into it.

4.2. Effect of water stress on grain yield

Yield reduction due to water deficit varies from year to year in rainfed lowland rice growing areas with erratic rainfall, and the degree of yield reduction depends on the intensity, timing and duration of drought. The disappearance of field water particularly flowering time results in a large yield reduction (Jearakongman et al., 1995). A number of previous studies on the effect of water stress on grain yield in lowland rice have reported large variation in yield reduction. For example, Pantuwan et al. (2002) measured 19% yield reduction under mild drought up to 81% under severe drought in experiments that managed drought and well-watered field condition in Northeast Thailand. The large yield reduction occurred in the fields exposed to prolonged severe drought during the flowering to grain filling period. A similar result was reported by Ouk et al. (2006) in artificially induced drought conditions in Cambodia (12–46% yield reduction). However, under the farmers practice of field management, yield reduction is generally smaller than those experimental conditions where drought was artificially induced by draining water from the field. For example, Tsubo et al. (2009) estimated moderate yield reduction (up to 22% for photoperiod-sensitive long-maturing cultivars) responding to mild drought in a multi-year and multi-location experiment in Cambodia. The yield reduction simulated in the present study (up to 36% in 2007) is of similar magnitude to the field study of Tsubo et al. (2009), but the actual yield reduction would depend on the timing and amount of rainfall in the simulated season (Inthavong et al., 2011b). With regard to spatial distribution, the simulated yield reduction was larger in the western zone (12%) than in the central and eastern zones (4% and 6%, respectively) of the province. This was mostly associated with the geographical gradient of field water availability, as annual rainfall decreases from the southern and north-eastern parts of the province to the north-western corner of the province where rainfall is the lowest (Inthavong et al., 2012).

Thus, according to the present simulation study, as well as experimental results, yield reduction due to water stress during crop growth may be rather modest in rainfed lowland rice in central Laos. However, two points need to be pointed out; one is that terminal drought stress, i.e., continuous drought stress to the expected crop maturity, can cause a severe yield reduction if late maturing or photoperiod sensitive varieties were used however, generally terminal drought problems have become less severe with the introduction of both photoperiod insensitive, quicker maturing varieties and earlier planting times (Fukai and Ouk, 2012). The second point is that early season drought is common in the Mekong region, and this prevents farmers seeding or transplanting seedlings at an appropriate time, however these aspects were not considered in the simulation study or the experimental work quoted here.

4.3. Effect of nutrient input on grain yield

Compared to rather modest effect of drought stress that develops during crop growth, the simulation study indicated a large effect of nutrient stress on grain yield. The present study shows that the yield under no fertilizer application is almost half that achieved under the recommended rate of fertilizer application and less than one third of the yield under unlimited nutrient conditions. The simulated effect of nutrient omission from the recommended fertilizer rate matches with the published work of Linquist and Sengxua (2001) as shown in Table 4. Further, in the work at a village within the western zone of Savannakhet province, Inthapanya et al. (2000b) reported 50–75% yield increase from around 1.2 t ha^{-1} to 1.8–2.1 t ha^{-1} with the recommended fertilizer application. The simulated yield without fertilizer application under water limitation in the western districts in the 2007 wet season (1.6 t ha^{-1}) was 33% higher than the yield (1.2 t ha^{-1}) reported by Inthapanya et al. (2000b). The Savannakhet weather station, which is located in the western zone, registered about 100 mm in October in the years (1996 and 1997) when Inthapanya et al. (2000b) conducted the experiments, while October rainfall was over 300 mm in the year when the present study was conducted. This implies that the yield difference could be due to the difference in field water availability in the late growing season. The simulated yield in the present study under inherent nutrient supply without water stress was low at 1–2 t ha^{-1} in more than 75% of the total rice growing areas. The importance of fertilizer application was further emphasized by Linquist and Sengxua (2001), who reported that the recommended fertilizer application significantly increased yield in most rainfed lowland rice fields in the central region, where Savannakhet province is located, to southern Laos. Similarly, the fertilizer application rate was found to be important in determining crop yield, as demonstrated in the 2011 dry season in the present study. This conclusion was supported by the positive relationship between N and P fertilizer rates and yield among 101 farms surveyed in the two year study in Savannakhet (Inthavong et al., 2011a).

There was variation in inherent nutrient supply and yield without fertilizer application across the province; hence a blanket recommendation of fertilizer application rate is unlikely to be effective in achieving high returns. More refined fertilizer application recommendation appears possible and promising; for example, the relatively low yield under inherent nutrient supply (913 kg ha^{-1}) in Outhomphone (4) district reflects an inadequate inherent soil nutrient supply (12.6 kg N ha^{-1} and 2.5 kg P ha^{-1}). Therefore, to achieve a yield target at 3 t ha^{-1} in Outhomphone would require a medium rate of 60 kg N ha^{-1} and 26 kg P ha^{-1} fertilizers. In contrast, almost all fields in Champhone (5) district would require only 30 kg N ha^{-1} and 5 kg P ha^{-1} to achieve the same yield level. Therefore, fertilizer recommendation at the district or village level would be useful for rice producers to ensure application of appropriate rates of inorganic fertilizers for increasing rice yield. With regards to the nutrient requirements of rice in the rainfed lowlands, yield is more responsive to applied fertilizer under favorable water environments compared to drought-prone environments (Wade et al., 1999). It can be recommended that low or no fertilizer is applied to rainfed lowlands with high drought risk, i.e. upper toposequence fields, while appropriate fertilizer application can be recommended for low drought risk areas, i.e. lower toposequence fields (Haefele and Konboon, 2009; Haefele et al., 2010). In addition, there are several sound techniques of nutrient management to improve productivity of rainfed lowland rice. For example, splitting N fertilizer applications into several at various growth stages (e.g. transplanting, tillering and panicle initiation) enhances the yield, compared with the fertilizers applied only at transplanting (Linquist and Sengxua, 2003), and the use of organic residues such as rice straw and hulls improves the yield response to fertilizer inputs as well as inherent soil nutrient supply (Linquist et al., 2007). These agronomic techniques are important for rainfed lowland rice ecosystems under limited soil nutrient condition, such as in the lowlands in Savannakhet province.

5. Conclusion

The soil water balance model was linked with the soil nutrient model, and then the combined model, which requires fewer sets of input data to run than most current rice models, was applied to estimate rice yield for the rainfed lowlands in Savannakhet province, Laos. The model generally performed well in predicting crop yield levels, as the simulation results were similar to both the observed farmers' yield data, collected from a wide range of soil and climatic conditions throughout the province, and also similar to yield response to fertilizer rates under experimental conditions. The simulated results confirmed that the low rice yield often observed in the province was associated with low inherent nutrient supply, particularly of N and P. Thus, application of N and P fertilizers can be expected to increase grain yield but the response would depend on inherent soil fertility and water availability conditions. The information on fertilizer requirement to achieve specific yield targets can be useful in helping rice farmers, as well as the district or provincial agriculture and forestry extension sectors, in formulating appropriate and effective recommendations on the use of inorganic fertilizers in rice field in different areas in each district of Savannakhet province.

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ສາທາລະນະລັດ ປະຊາທິປະໄຕ ປະຊາຊົນລາວ

ສັນຕິພາບ ເອກະລາດ ປະຊາທິປະໄຕ ເອກະພາບ ວັດທະນາຖາວອນ

ກະຊວງກະສິກຳ ແລະ ປ່າໄມ້

ກົມປູກຝັງ

ຍຸດທະສາດພັດທະນາການປູກຝັງ
ຮອດປີ 2025 ແລະ ວິໄສທັດ ຮອດປີ 2030

<u>ວິໄສທັດຍຸດທະສາດ</u>

ປູກຝັງທັນສະໄໝ ສະອາດ ປອດໄພ ໃສ່ໃຈຄຸນນະພາບ ໝັ້ນຄົງ ຍືນຍົງ ເປັນສິນຄ້າ

ນະຄອນຫຼວງວຽງຈັນ, ກຸມພາ 2015

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Soil clay content, rainfall, and toposequence positions determining spatial variation in field water availability as estimated by a water balance model for rainfed lowland rice

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Abstract. Drought is a major limiting factor for the production of rainfed rice in the Mekong Region. Thus, estimation of the length of growing period (LGP) based on estimation of the development of water deficit is essential for sound planning of agricultural development. A recently developed soil-water balance model was used to quantify the availability of water for rice crops and yield reduction due to water deficit. Field water availability is known to be largely affected by soil type and rainfall pattern, and their separate effects were investigated in this study of a spatial analysis of LGP, using inputs for rainfed lowland rice in Savannakhet province in central Laos. The analysis showed that the start of growing period (SGP) and end of growing period (EGP) were affected largely by geographical variations in rainfall and soil clay content, respectively. Also, the areas having relatively short LGP were generally associated with large yield reduction because of low water availability associated with coarse-textured soils. At local scale, field water availability varied from upper to lower positions of a sloping land (toposequence) in the rainfed lowland ecosystem of the Mekong region, causing variation in yield within the toposequence. Using the level of field water determined around flowering time at different toposequence positions in 45 farms, estimated yield reduction was compared in seven main rice-growing districts of the province. Variability of yield loss, associated with variation in water availability, was larger across the toposequence positions than across districts, showing the importance of local variability in determining yield in rainfed lowland rice. The present approach of a combination of simulation model and GIS is adopted for characterisation of the water environment for rainfed lowland rice in other parts of Laos, as well as in neighbouring Thailand and Cambodia.

Additional keywords: agro-ecological zone, drought, GIS, growing period, *Oryza sativa*.

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Introduction

Rice (*Oryza sativa* L.) is the most important food crop in the Mekong region. Rice is grown in rainfed lowland, irrigated lowland, and rainfed upland conditions, but rainfed lowland cropping is the most common (Mackill *et al*. 1996; Wade *et al*. 1999). In Laos, for instance, two-thirds of the total rice-growing area and 80% of production is in the rainfed lowland environment (Schiller *et al*. 2001). Rice yield in the rainfed lowland environment in the region is constrained by the uneven distribution of rainfall in the wet season (Inthapanya *et al.* 1996). Thus, better quantification of the availability of water for rice growth is important for improving the productivity of rainfed lowland rice. In regions where rice productivity depends on field water availability, characterisation of the length of growing period (LGP) and of water stress development can provide the geographical dimensions of soil hydrological patterns for various growing environments (Inthavong *et al*. 2011*a*).

There has been little success in using LGP to define agro-climatic zones for the rainfed lowland rice ecosystem in the Mekong region. Inthavong *et al*. (2001), for example, carried out the first study on agro-ecological zoning for crop suitability in Laos; they employed the FAO (1996) approach, linking it to the geographic information system (GIS) to define the LGP zones for rainfed lowland rice. However, this FAO approach to the classification of LGP is based solely on a simple climatic model that determines the number of days when precipitation is equal to, or greater than, half the potential evapotranspiration (Chapman 2001). It may not be reliable for the rainfed lowland rice environment, as it does not take account of soil water characteristics such as water-holding capacity, field water loss through runoff, and downward and lateral water movement, all of which can have a significant impact in determining the water availability for rainfed lowland rice (Bouman *et al*. 2001; Chen *et al*. 2002; Tsubo *et al*. 2007*a*). It also does not estimate or take into account the amount of stored water carried forward from one day to the next within the season, despite the fact that there can be a long period with standing water in rice paddy fields. A recently developed soil-water balance model has overcome the limitations mentioned above, and was successfully validated with several field water determinations conducted in Savannakhet Province in central Laos (Inthavong *et al*. 2011*b*).

Previous studies from the Mekong region have reported on edaphic and climatic factors that influence field water availability for rainfed lowland rice (Tsubo *et al*. 2007*b*, 2009; Inthavong *et al*. 2011*b*). Water availability is higher with fine-textured rather than coarse-textured soil but fluctuates with rainfall throughout the growing season. Comparison of a few locations with varying soil clay content using 20 years of rainfall data showed that soil clay content has a large effect on the end of growing period (EGP), whereas large variation in the start of growing period (SGP) is mostly associated with variation in rainfall occurring at the early part of the growing season (Inthavong *et al*. 2011*a*). However, the separate effect of soil types and rainfall patterns on spatial variation in growing period is not known.

Rice crops in the region are typically cultivated in a series of paddy fields on a sloping land, i.e. a toposequence. In high toposequence positions, water losses by percolation and seepage are large, so water availability tends to be lower (Tsubo *et al.* 2006, 2007*a*; Inthavong *et al*. 2011*b*). In soils with low clay content, the trend is for increasing water availability at the lower parts of the toposequence (Samson *et al*. 2004; Boling *et al*. 2008). As a result, when growth is constrained by water availability, the rice yields are higher in the lower parts (Homma *et al*. 2003). The variation in water availability and hence yield across toposequence positions at a local level needs to be compared with the variation at a larger scale across different districts within a province so that the accuracy of GIS maps at the larger scale can be evaluated.

The objectives of this study were therefore (*i*) to map the LGP in order to conduct a spatial analysis of LGP to examine the separate effects of soil clay content and rainfall variability, and (*ii*) to compare the variation in yield reduction due to water deficit around flowering time between large-scale geographical variation (e.g. among districts within a province) and small-scale local variation at different toposequence positions.

Materials and methods

Study area

The study focussed 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). This province has the largest area of lowland rice of any province in the country, accounting for 23% of the lowland rice area (599 000 ha) in 2004. The rainfed lowlands in the province suffer chronic drought and were therefore selected for the case study.

Climate

The province is subject to a monsoonal climate, with the south-west monsoons being associated with distinct wet (May–October) and dry (November–April) seasons. August is usually the month with the highest rainfall, receiving an average of 354 mm with a range of 131–565 mm over the 20 years 1985–2004. The median annual rainfall (based on 50% cumulative probability) shows that rainfall decreases from the southern (1400 mm) and north-eastern (1400 mm) parts of the province, to the north-west (1100 mm) (Fig. 1*a*). Rice is grown mostly in the western half of the province. Seeds are generally sown in the nursery in late April–May. The mean monthly rainfall for April (i.e. before seeding) is around 25–50 mm except in the north-west, where rainfall is <25 mm, and in the central south-west, where monthly rainfall exceeds 50 mm (Fig. 1*b*). In October just before rice maturity, most of the rice-growing area has <25 mm rainfall, except in south-western areas, where the rainfall is 25–50 mm (Fig. 1*c*). Mean weekly potential evapotranspiration (PET) based on estimates using the FAO Penman–Monteith model (Allen *et al.* 1998) is 30 mm/week with a range of 24–38 mm/week during the growing period; the eastern part of the province has a slightly higher PET (33.7 mm/week) than the western part (32.8 mm/week) (Inthavong 2009).

Soil type

In the period 1996–2000, the Soil Survey and Land Classification Centre (SSLCC) of Laos collected a total of 339 soil sample profiles throughout Savannakhet Province and analysed them for soil physical and chemical properties (Phommachak and Vonghachak 1996). It is assumed here that the soil physical parameters have not changed, since the agricultural land use practice has not changed much from the time of the sampling. Soil clay content measured from these samples was used for soil water balance and subsequent GIS mapping of the LGP in this study. The samples were mainly taken from agricultural land at a sampling density of about one soil pit to every 50–100 ha. The classification of land-use types for Savannakhet Province by clay content (Table 1; original data from SSLCC 1996) shows that >80% of the total agricultural land in the province is associated with soils with a low clay content. Overall, soils with clay contents of 7–12% and 0–7% occupy 36.7% and 31.5% of the province, respectively. The geographical distribution of soils with different clay contents is illustrated in Fig. 2. Rice paddy fields in the province are mainly on soils with clay contents <12%. A large proportion of the rice fields in the north-west, central, south and south-western part of the province have clay content <7%, and overall comprise ~20% of the total agricultural land in the province.

Model description

The water balance model used in this study has been described in detail by Inthavong *et al*. (2011*a*), so only a brief description is given here. The water balance is computed for the surface layer, which consists of standing water and the topsoil layer, and then for the subsoil layer. Components of the water balance in the surface layer are rainfall (measured), PET estimated using the FAO Penman–Monteith model (Allen *et al*. 1998), downward water loss as determined from the clay content of the topsoil (Tsubo *et al*. 2007*a*), and surface runoff when the free water level exceeds the height of the bund. In the subsoil layer, the water balance comprises input water from the topsoil layer (i.e. downward water loss) and deep percolation loss, which is determined from clay content of the subsoil. When subsoil is fully saturated, the deep percolation loss plus lateral water

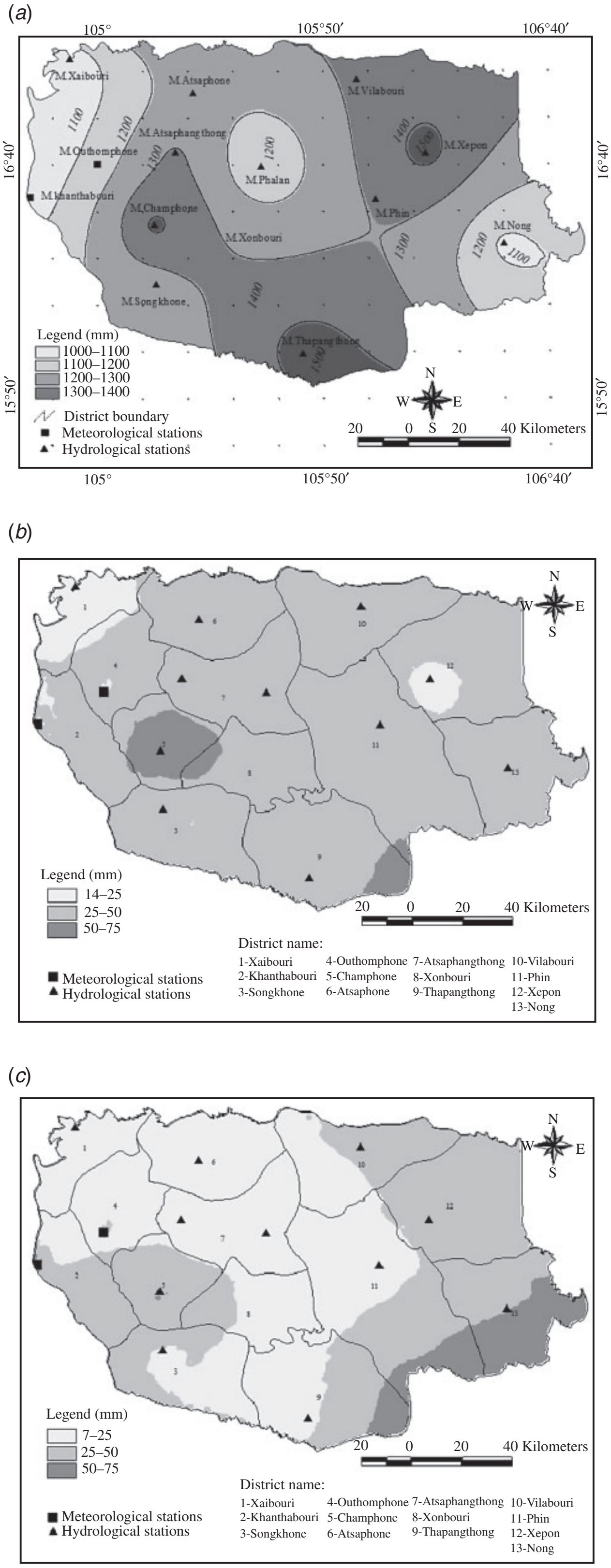

Fig. 1. Median rainfall distribution contour maps, representing 50% cumulative probability level of occurrence of rainfall event for Savannakhet Province, Laos: (*a*) annual, (*b*) April, (*c*) October.

movement from the subsoil layer is assumed to equal the downward water loss from the surface layer. The soil moisture content under air-dry condition was used as the initial soil water content of the topsoil layer at the start of a simulation run to estimate daily or weekly field water storage during the growing season (e.g. April–November).

For determining LGP, SGP was defined as the time when three continuous weeks of field water storage within the surface layer was greater than field capacity, while EGP was defined as the time when the amount of water storage within the surface layer was lower than wilting point. The LGP was then determined by the duration of the period between SGP and EGP.

Simulation procedures

Comparison of LGP with different methodologies

A comparison of two methodologies for estimating LGP, i.e. the soil water balance model and the FAO methodology (rainfall >1/2PET), was carried out by first running the water balance model with different sets of climatic inputs: (*i*) weekly rainfall for 20 individual years in the period 1985–2004, and (*ii*) weekly mean and median rainfall for the period 1985–2004. The mean of the 20 LGPs from these individual year simulations, the LGP results from the dry and wet years (2000 and 2003, respectively), and the results from using the weekly mean and median climatic inputs were then compared with estimates based on the FAO methodology using long-term mean climatic data recorded for the same period, 1985–2004. The soil parameters used were based on data obtained from rice fields in Phonsim Nua village (16°35′N, 104°53′E) in Khanthabouri district, where the soil was classified as a loamy sand with an average topsoil and subsoil clay content of 8.8% and 21.7%, respectively.

Mapping growing period

The water balance model was executed in a user-friendly spreadsheet (Microsoft® Excel using the macro programming language), coupled with raster-based GIS (ArcView GIS3.2a) running with the inputs of median weekly climate events (i.e. rainfall and PET), presenting as 50% cumulative probability level of rainfall and PET in each week, and soil water characteristics for two pathways (point-based and gridded surfaces at weekly intervals).

The model computes weekly field water storage, SGP, and EGP, and subsequently LGP at point locations by first using soil information from 339 soil profile samples obtained from the soil database for Savannakhet Province (SSLCC 1996), together with the median weekly rainfall and PET of the period 1985–2004, obtained by spatial interpolation function in GIS, namely variography and kriging (Goovaerts 1997), to generate the weekly rainfall surfaces at 5-km cell resolution for 52 weeks, using rainfall data derived from a total of 62 locations; 43 locations were within the country (33 meteorological and 10 hydrological stations), and 19 were meteorological stations in nearby north-east Thailand. Rainfall data from Vietnam near the Lao border were not included in the dataset because the rainfall pattern in Vietnam is believed to be different from Laos. This is caused by the chain of the Annamite Mountains, creating a rain shadow effect in the Lao side. In addition to this, most of the north-eastern edge of Savannakhet Province bordering Vietnam

Table 1. Classification of land use types by soil clay content in Savannakhet Province, Laos (original data from SSLCC 1996)

Clay	Agricultural land		Forestland		Grassland		Others		Total	
(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
0–7	119 444	5.8	549 000	25.7	175	0.01	6069	0.29	688 750	31.5
7–12	90 221	4.3	674 138	31.5	4538	0.21	17 488	0.82	804 062	36.7
12–20	30 132	1.5	540 769	25.3	4913	0.23	5781	0.27	595 656	27.2
20–27	3170	0.2	88 042	4.1	306	0.01	581	0.03	29 325	4.3
>27	1219	0.1	3925	0.2	–	–	156	0.01	5300	0.2
Total	244 185	11.8	185 5873	86.7	9931	0.46	30 075	1.4	214 0065	100

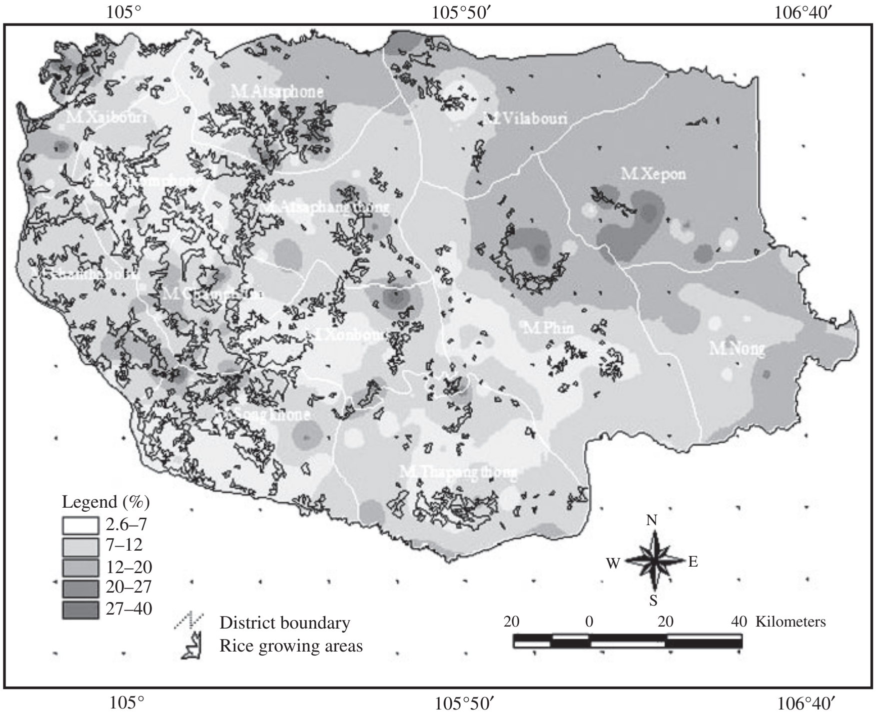

Fig. 2. Soil clay content map of Savannakhet Province, Laos (NAFRI 2000).

is not utilised for lowland rice cultivation, as the areas are mostly rolling hills with slopes >16%. The median weekly climate for PET was interpolated by using radial basis interpolation function at 22 Lao meteorological stations where all the required weather data were available for the period 2000–2004 (some stations had data for the period 1985–2004). The simulated results of LGP, SGP, and EGP at different locations were then interpolated to create gridded surface maps of LGP, SGP, and EGP for the entire province.

Estimating separate effects of soil clay content and rainfall on growing period

The water balance model was run to investigate which of the two main factors, soil type or rainfall pattern, has a greater impact on SGP and EGP and, hence, LGP. The study was conducted by using soil clay content and rainfall pattern for two analysis pathways. First, the soil-water balance model was run to compute the LGP for different soil types with contrasting clay contents, using the standard rainfall throughout the province; the aim was to determine the effect of soil clay content on LGP. For this purpose, the median weekly long-term rainfall for the whole of Savannakhet was used as a standard rainfall input. Second, to investigate the effect of rainfall on LGP, the model was run using median weekly rainfall surfaces at 5-km cell resolution for 52 weeks for the province, with the soil type kept constant using topsoil and subsoil clay contents of 12% and 25%, respectively (the mean clay contents for the whole province).

Estimating the importance of toposequence position relative to large-scale geographical variation

Yield reduction (YR) due to water deficit was estimated using a linear equation developed by Ouk *et al.* (2006): YR (%) = $-1.68 WL_{REL}$ (cm), where WL_{REL} (<0) is relative field water level (FWL) [i.e. the mean of FWL only when water condition is below the soil surface (FWL <0)] around flowering time (6 weeks, i.e. 3 weeks before and after flowering date). We used the flowering time of Lao standard cultivar TDK1 for estimation of WL_{REL}. We used this equation in two ways: one with soil water level estimated using the simulation model, and the other with measured soil water level in the field. In the first study, this equation was incorporated into the soil-water balance model using soil information obtained from 53 soil profile samples from main rice-growing areas in seven districts within the province (Atsaphangthong, Champhone, Khanthabouri, Outhomphone, Songkhone, Xaibouri, and Xonbouri), together with the 2008 gridded rainfall surface map (2008 was used as we measured soil water level at several farms, as described below) generated from rainfall data recorded at the 62 locations mentioned earlier. Once the flowering date was defined and matched with the corresponding WL_{REL}, the spatial variation in YR was estimated.

In the second study, YR was estimated using FWL data measured in farmers' paddy fields. The measurements of FWL are described in detail by Inthavong *et al*. (2011*b*), so only a brief description of the field measurements is given here. Using perforated PVC tubes with a diameter of 100–150 mm and length of 350 mm (and 5-mm-diameter holes in the bottom 100 mm), daily FWL above or below the soil surface was measured in 2008 for top, middle, and bottom toposequence positions in 45 farmers' fields across the seven districts. The number of farms in each district varied from three to 11. Considering the number of farms as replications, a two-way ANOVA with the Tukey test was conducted to examine variation in YR across districts and toposequential positions.

Results

LGP with different methodologies

The estimates of LGP using the different methodologies are summarised in Table 2. The results show some differences in SGP, EGP, and LGP with respect to the methodology used. The LGP results with the climate data for individual years indicated considerable year-to-year variability as shown for the two extreme years (2000 and 2003). However, the mean SGP, EGP, and LGP, estimated from the results of individual years, are similar to those based on the use of mean climatic data as inputs. The estimates based on the long-term means of climatic data differ from those based on individual years by only 1 week. The use of median rainfall data resulted in a 1-week delay in the start of, and a 1-week earlier finish to, the growing period, giving an overall shorter LGP by 2 weeks. When the FAO methodology was used to estimate LGP, the growing period tended to start and also end earlier than for estimates based on the soil-water balance method (Table 2). An exception to this was for the year 2000, in which high early rainfall resulted in an early start to the growing period.

Effects of soil clay content and rainfall on growing period

When SGP was estimated under standard, long-term rainfall inputs throughout the province but actual soil type (clay content), there was almost no effect of soil type on SGP, which varied between weeks 19 and 21 (i.e. in May) of the year (Fig. 3*a*). When the model was run with a standard soil type and actual rainfall data, on the other hand, SGP varied greatly, from week 19 to week 27 (Fig. 3*b*). Growing period commenced in weeks 19 and 21 in most areas, but in areas of the north-west, south-western corner, and central north, SGP was delayed by 2–4 weeks. The SGP pattern estimated from actual soil and rainfall data had the largest variation (Fig. 3*c*), and it tended to follow the pattern of SGP variation obtained under actual rainfall and standard soil type. Thus, the central south had the earliest SGP, with gradual delay towards the northern part, particularly the central north of the province, although south-western corner was also delayed in SGP.

The effect of soil type on EGP under standard rainfall throughout the province was rather large, resulting in an EGP range between weeks 39 and 47 (Fig. 4*a*). The growing period finished earlier (before week 43) in some areas in the north-west, south-west, and central south, where soils with a coarse texture (<7% clay content) predominate, relative to large areas of the west and central south-west of the province, which have soils with >7% clay content (Fig. 2). Under the standard soil type but with actual rainfall patterns, the EGP varied between weeks 43 and 47 for most rice-growing areas, with the growing period ending later in the south-west (Fig. 4*b*) where October rainfall was generally higher (Fig. 1*c*). With actual rainfall and soil type as inputs, the EGP variation (Fig. 4*c*) reflected more in variation in soil type (Fig. 2) and hence the EGP map in Fig. 4*a*, although the delaying effect of high late-season (October) rainfall in the south-west (Fig. 1*c*) can be also seen in Fig. 4*c*. Thus, EGP was before week 41 in some areas of the north-west, while most of the central part of the province had EGP between weeks 41 and 43, and some areas in the south and west between weeks 43 and 45.

Table 2. Comparisons of simulated results for the start, end, and length of growing period (SGP, EGP, and LGP, respectively) for rice planted in Phonsim Nua village (16°34′N, 104°51′E), Khanthabouli district, Savannakhet Province, Laos

	Soil-water balance method					FAO
	Single-year climate data			Long-term climate data		
	Mean from individual years[A]	Wet (2000)	Dry (2003)	Mean[B]	Median[C]	Mean[D]
SGP (week of year)	19	16	20	19	20	16
EGP (week of year)	45	45	43	46	44	42
LGP (weeks)	27	30	24	28	25	27

[A]Mean of simulated results using inputs from individual years (1985–2004).
[B]Using mean long-term climate data (1985–2004).
[C]Using median climate event (estimate based on 50% probability level of climate data 1985–2004).
[D]FAO methodology: rainfall >1/2 PET using mean climate data (1985–2004).

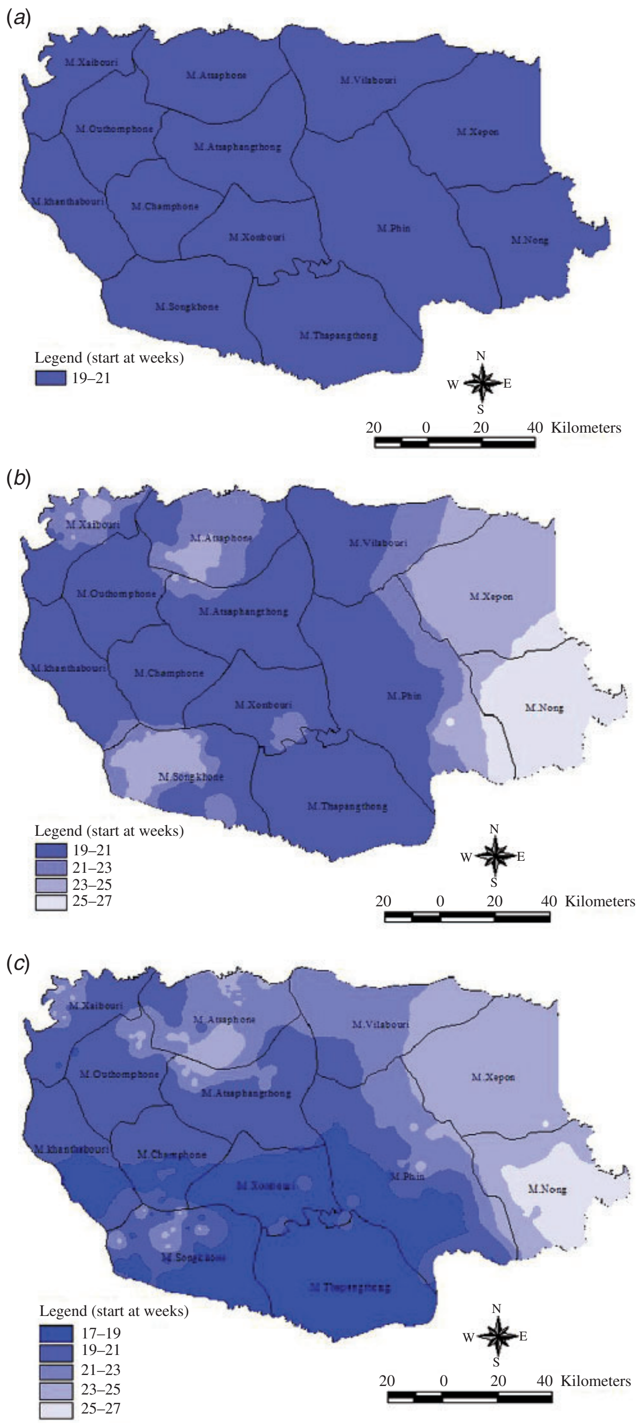

Fig. 3. Start of growing period (SGP), as estimated by the soil-water balance method using: (*a*) standard rainfall and actual soil types, (*b*) actual rainfall and standard soil type, and (*c*) actual rainfall and actual soil types, for Savannakhet Province, Laos.

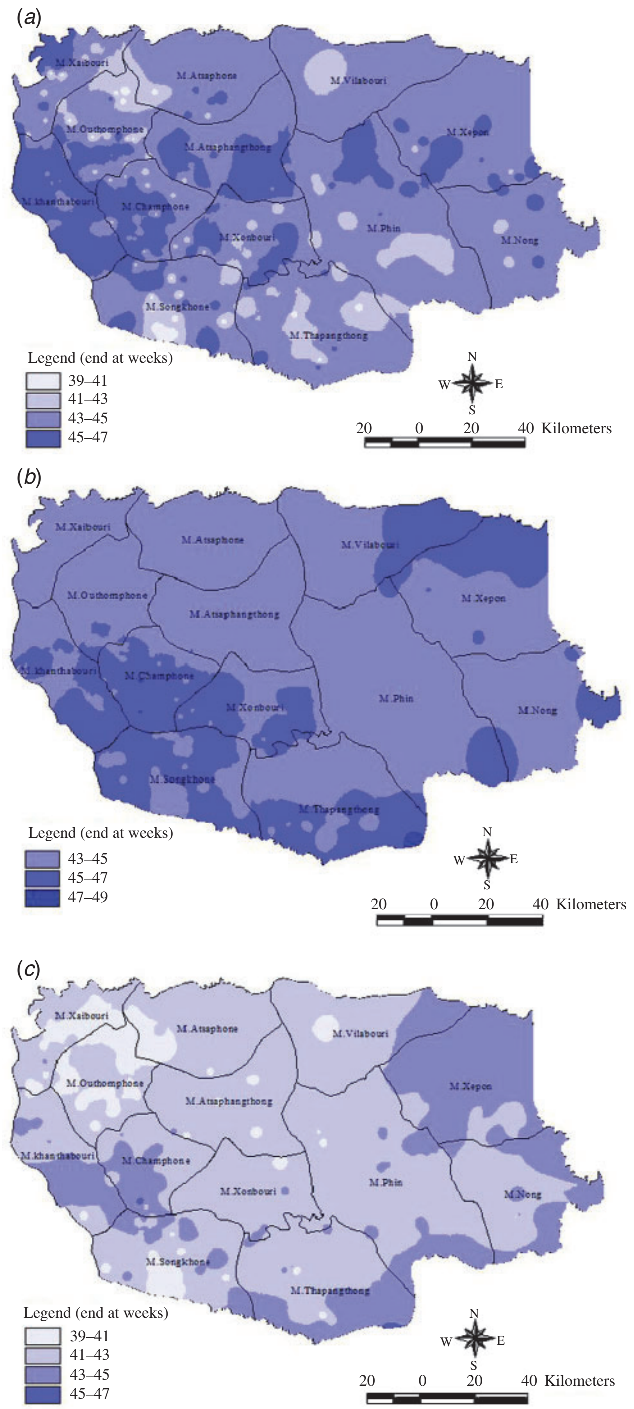

Fig. 4. End of growing period (EGP), as estimated by the soil-water balance method using: (*a*) standard rainfall and actual soil types, (*b*) actual rainfall and standard soil type, and (*c*) actual rainfall and actual soil types, for Savannakhet Province, Laos.

The effect of soil type on LGP was large, with differences of up to 10 weeks in the main rice-growing area of the province (Fig. 5*a*). As there was almost no effect of soil type on SGP, the LGP map here reflected the map of EGP in Fig. 4*a*. Rice fields on soil types with clay content <7% in the north-west and south-west had LGP of 21–25 weeks, this being considerably shorter than for other soil categories in the province. When the model was run with the standard soil type and actual rainfall, a short LGP of <21 weeks was associated with the areas in the central north and the north-western corner, while the remaining areas had

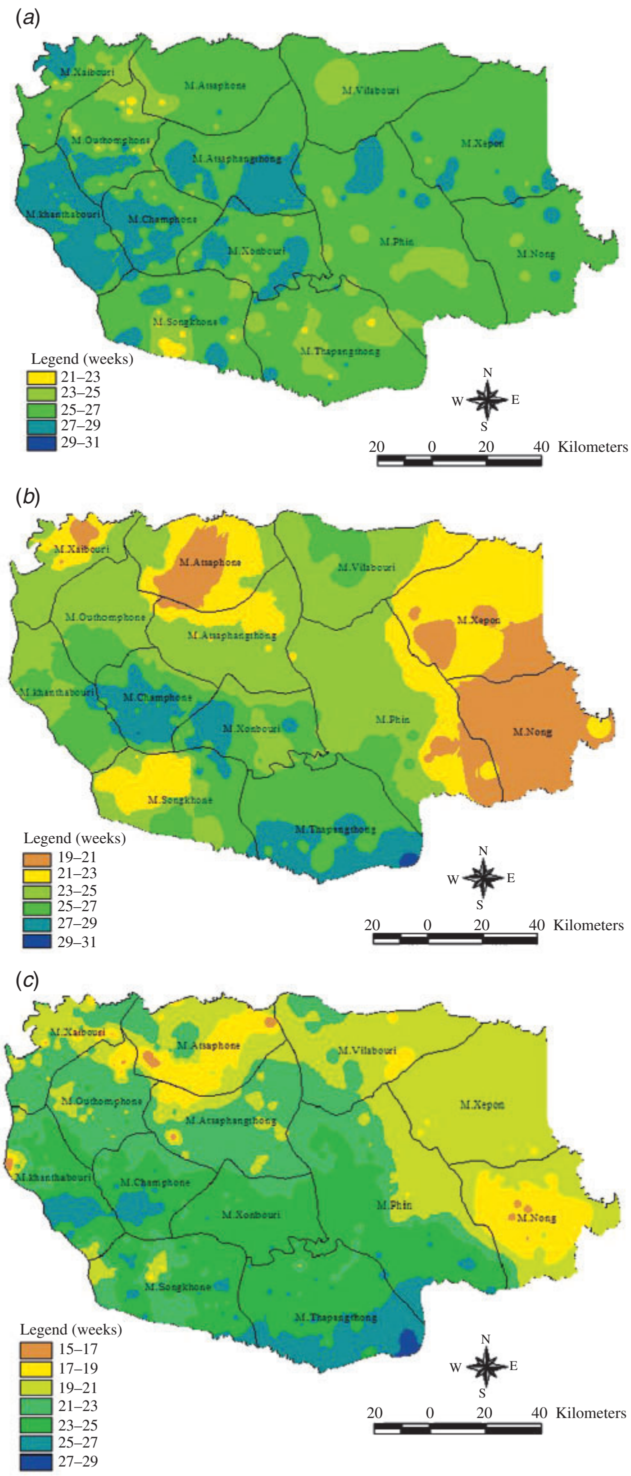

Fig. 5. Length of growing period (LGP), as estimated by the soil-water balance method using: (*a*) standard rainfall and actual soil types, (*b*) actual rainfall and standard soil type, and (*c*) actual rainfall and actual soil types, for Savannakhet Province, Laos.

intermediate LGP ranging between 21 and 25 weeks; an exception to this was in areas in the south and central south-west, which had long LGP of >25 weeks (Fig. 5*b*). With actual rainfall and soil types as inputs, variation in simulated LGP was large (Fig. 5*c*), ranging from 15 to 29 weeks. This reflected in LGP patterns determined by variations in both rainfall and clay content.

LGP zones in Savannakhet province

Based on an analysis of the above results that used median weather data available from the meteorological stations of the province, the agricultural land in the seven districts where actual water level was determined, mostly lying in central and western Savannakhet province, can be delineated into three main LGP zones (Table 3). The short LGP zone (<21 weeks) covers most of the area in Xaibouri district and one-third of the area of Atsaphangthong district. These lowland areas are likely to be subjected to lower rainfall (Fig. 1) and have soils with relatively low clay content (Fig. 2). The intermediate LGP zone (21–25 weeks) occupies almost all areas in the districts of Outhomphone and Xonbouri. Most areas of the districts of Atsaphangthong, Champhone, Khanthabouri, and Songkhone also belong to this zone, and >75% of the total area of the seven districts is classified into this zone. The long LGP zone (>25 weeks) mainly covers Champhone district, as well as the districts of Khanthabouri and Songkhone. Field water availability is favourable in this zone on account of relatively high rainfall (Fig. 1), and the soils having comparatively high clay content (Fig. 2), which enables them to hold more water and reduce the possibility of water stress at the end of the growing season.

Effect of toposequence position relative to large spatial variation

As shown in Table 4, the yield loss estimated from the water levels determined in 2008 was larger for rice fields in the districts of Outhomphone and Atsaphangthong than in the districts of Champhone and Songkhone ($P < 0.01$). Observed FWLs during flowering time were low in rice fields of Outhomphone and Atsaphangthong districts, and these are the districts where the fields tended to have relatively shorter LGP than those of Champhone and Songkhone districts (see Fig. 5*c*). At a local scale, the FWLs were generally lower at the top position of the toposequence than the middle and bottom positions, and the yield reduction was estimated to be larger for the top position in all districts, except Atsaphangthong where the yield loss was estimated to be higher at the bottom position (Table 4). Overall, crop water deficit was significantly more severe for the top position of rice fields than for the other two toposequence positions ($P < 0.01$). The variance ratio for the effect of toposequence position ($F_{2,114} = 12.87$) was higher than for the effect of district ($F_{6,114} = 9.32$), indicating that toposequence positions contributed more to the variation in yield reduction.

The simulated results of yield limited by water deficit for the 2008 rice-growing season show that the yield reduction was greater than that based on observed FWL, but that Outhomphone district encountered severe water deficit in response to late-season drought which caused simulated yield reduction of 29%, followed by Xonbouri and Atsaphangthong (Table 4). Therefore, rice yield in Outhomphone district was

Table 3. Areas (ha) for different zones of the length of growing period (LGP) (short, intermediate, and long) estimated from median rainfall of long-term data across seven districts of Savannakhet Province, Laos

Values in parentheses are the proportion of the district's area within the LGP zone

District	Location in province	Short: <21 weeks	Intermediate: 21–25 weeks	Long: >25 weeks
Atsaphangthong	Central	6856 (35%)	12 869 (65%)	–
Champhone	Central south-west	–	28 038 (63%)	16 813 (37%)
Khanthabouri	West	381 (2%)	17 344 (72%)	6300 (26%)
Outhomphone	Central north-west	944 (3%)	30 094 (97%)	–
Songkhone	South-western	2106 (5%)	31 375 (80%)	5856 (15%)
Xaibouri	North-western	13 175 (66%)	6719 (34%)	–
Xonbouri	Central	–	14 275 (92%)	1306 (8%)
Total		23 462 (12%)	140 714 (72%)	30 275 (16%)

Table 4. Yield reduction (%) estimated based on observed field water levels for rainfed lowland rice in different toposequence positions (top, middle, and bottom) in the 2008 wet season, across the main lowland rice fields in seven districts of Savannakhet province, Laos

Corresponding yield loss from simulated results for the middle toposequence position is also shown. Means followed by the same letter for different districts or for different toposequence positions are not significantly different at $P = 0.05$

District	No. of farms	Observed yield reduction				Simulated yield reduction
		Top	Middle	Bottom	Mean	Middle
Atsaphangthong	7	8.1	7.9	10.9	9.0a	17.4
Champhone	11	0.1	1.0	1.2	0.8b	0.7
Khanthabouri	4	20.3	4.5	0.0	8.3ab	5.0
Outhomphone	7	24.9	9.1	5.3	13.1a	29.0
Songkhone	7	0.0	0.0	0.7	0.2b	3.6
Xaibouri	3	14.7	0.0	0.0	4.9ab	0.0
Xonbouri	6	8.8	8.3	4.5	7.2ab	20.5
Mean		11.0a	4.4b	3.2b		10.9

estimated to be more severely affected by drought, although the district had mostly intermediate LGP.

Discussion

The results of the study (Table 2) show the usefulness of the simulation based on the use of climate data for individual years compared with those based on the use of mean climate data, because the former provides the probability of variability in LGP, SGP, and EGP across years due to rainfall variability. However, such simulation studies require long-term climate data from a large number of meteorological stations (cf. only two meteorological stations with long-term climate data available in Savannakhet Province). The simulation using mean climate data provided similar results to the mean of LGPs for individual years; however, the use of mean rainfall data may be less reliable because the occurrence of large rainfall events increases mean rainfall, but they are not effective in increasing soil water availability to the crop. Median climate input was used in most simulations in this study because, unlike the use of mean values, it can take account of an excessively high rainfall event. The concept of reliable rainfall was also introduced by Kam *et al.* (2000); they defined annual rainfall with a probability level >0.75 as realistic rainfall in determining the humid period for the growing season for rainfed lowland rice.

The present study shows that the FAO approach estimated SGP and EGP to be earlier in the season for the typical lowland condition than the water balance simulation approach (Table 2). Similarly, for all lowland rice-growing areas in Savannakhet Province, Inthavong (2009) produced SGP, EGP, and LGP maps based on the FAO approach, showing a growing period which started earlier (between weeks 15 and 17) than that based on the soil-water balance method used in the current study (between weeks 17 and 27). A comparison of the two approaches also shows lower variation in EGP (between weeks 41 and 42) using the FAO approach compared with the soil-water balance method (between weeks 39 and 47), and long LGP (>25 weeks) using the FAO approach compared with the current study (Fig. 5*c*, mostly <25 weeks). Thus, different LGP results were obtained with the different methodologies, as the FAO methodology and the soil-water balance method have differing criteria for defining LGP. However, as the soil parameter (clay content) is an important factor in the determination of moisture availability for lowland paddies (Tsubo *et al*. 2007*a*) through its effect on downward water and deep percolation losses, the LGP estimates based on the soil-water balance method would be more accurate than the estimate based only on rainfall and PET (i.e. the FAO methodology).

Although rainfall has a large influence on field water stored, short LGP and an early finish of the growing season are also associated with low soil clay content in the area covered by the study. The shortest LGP was mostly associated with soils of low clay content and intermediate rainfall in the central north-west (Outhomphone district) of the province (Fig. 5*c*). The area with the shortest LGP in the central north-west is known to have a severe problem with drought, and low yields of <2 t/ha are common for rice crops grown on the coarse-textured soil in the fields (Manivong and Douangsavanh 2007). This contrasts with the high clay soil of rice fields in the central west (Khanthabouri district), which have long LGP and where high yields of >2 t/ha are recorded, even though these areas received similar rainfalls (Fig. 1*a*). Özdemir *et al*. (2000) also reported that the soil clay content was the most important soil property to influence water retention, as the clay particles play an important role in the adsorption and desorption of water molecules. In addition to the edaphic effect on LGP (and also EGP), late SGP is associated with low rainfall, particularly at the beginning of the wet season (Figs 1 and 3). Thus, areas with late SGP are considered to be those prone to early drought. Similarly, early EGP areas can be considered as those prone to late drought, and these areas can utilise quick-maturing varieties to escape the late-season drought (Fukai *et al*. 1999).

Areas with shorter LGP, e.g. Atsaphangthong district, are associated with greater yield loss (Table 4), resulting mostly from low clay, coarse-textured soils, and thus low field water availability. In contrast, the yield was not reduced in the areas with a longer LGP, e.g. Champhone district, because of potentially high water availability within a growing period. Thus, there is general agreement between LGP and estimated yield loss due to drought during the growing period based on field observation of water level. However, Outhomphone district, which had mostly an intermediate growing period (21–25 weeks) (see Fig. 5*c*), had a large yield reduction according to the 2008 growing condition (Table 4). This indicates that the characterisation of drought environment should not rely solely on the estimation of LGP. The present study further revealed that the variability of yield loss within a small catchment could be larger than the regional variation. This confirms the importance of characterising water environment on sloping land for rainfed lowland rice (Jongdee *et al*. 2006). While the current model is useful in estimating LGP and water deficit development within the cropping season at a large scale such as district level, the present study has shown that the model may need to be improved to cope with the large variation in water availability, and hence yield, within a sloping land within a relatively small area. This aspect could be modelled by estimating lateral water flow for different toposequence positions.

The approach taken in this study has shown factors that determine the length of growing season and drought environment. The maps produced are useful in identifying areas that are prone to drought. Thus, in the case study here, the Savannakhet Province can be delineated into three main LGP zones: a short LGP zone was defined in the central north-west, an intermediate zone was defined for most areas of the province, and a long LGP zone was defined for the south-western and western parts of the province. Crop management practices including variety selection may be adjusted according to these zones with different LGPs. Agricultural extension officers in each district may recommend appropriate crop management practices. Further, in some districts where the map indicates favourable growing environments but where rice may not be currently grown on a large scale, preliminary investigation may be made to cultivate rice. This present approach of combining the use of simulation model and GIS mapping has been extended to develop drought maps for other provinces in Laos, and then further to neighbouring Thailand and Cambodia.

Conclusion

The zoning maps of LGP, SGP, and EGP for rainfed lowland rice in Savannakhet Province were developed using a soil-water balance model run with the inputs of median weekly climatic data and soil water characteristics. The simulated LGP results based on the soil-water balance model were found to be superior to the FAO approach. Declining rainfall from the southern and south-eastern parts to the north-western corner of the province, and soil types with varying clay content, contributed to the classification of the LGP zones. Although clay content in soils and rainfall distribution pattern are both important factors influencing LGP, spatial variation in the SGP was due more to timing of initial wet season, while spatial variation in EGP was strongly dependent on soil clay content. The LGP zone maps can provide a geographical dimension of soil hydrological patterns for various rice-growing environments and also identify the spatial pattern of drought stress that is likely to occur. These LGP maps can be used to provide guidelines for determination of appropriate crop management strategies (e.g. time of planting, varieties). Also, quick-maturing, drought-tolerant varieties need to be developed to avoid late-season drought in areas with low clay content soils and in high toposequence positions (Fukai and Cooper 1995; Jongdee *et al*. 2006; Ouk *et al*. 2007). Therefore, the information generated in this simulation study is potentially useful for the formulation of strategies for the rice breeding program.

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Soil clay content, rainfall, and toposequence positions determining spatial variation in field water availability as estimated by a water balance model for rainfed lowland rice

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Abstract. Drought is a major limiting factor for the production of rainfed rice in the Mekong Region. Thus, estimation of the length of growing period (LGP) based on estimation of the development of water deficit is essential for sound planning of agricultural development. A recently developed soil-water balance model was used to quantify the availability of water for rice crops and yield reduction due to water deficit. Field water availability is known to be largely affected by soil type and rainfall pattern, and their separate effects were investigated in this study of a spatial analysis of LGP, using inputs for rainfed lowland rice in Savannakhet province in central Laos. The analysis showed that the start of growing period (SGP) and end of growing period (EGP) were affected largely by geographical variations in rainfall and soil clay content, respectively. Also, the areas having relatively short LGP were generally associated with large yield reduction because of low water availability associated with coarse-textured soils. At local scale, field water availability varied from upper to lower positions of a sloping land (toposequence) in the rainfed lowland ecosystem of the Mekong region, causing variation in yield within the toposequence. Using the level of field water determined around flowering time at different toposequence positions in 45 farms, estimated yield reduction was compared in seven main rice-growing districts of the province. Variability of yield loss, associated with variation in water availability, was larger across the toposequence positions than across districts, showing the importance of local variability in determining yield in rainfed lowland rice. The present approach of a combination of simulation model and GIS is adopted for characterisation of the water environment for rainfed lowland rice in other parts of Laos, as well as in neighbouring Thailand and Cambodia.

Additional keywords: agro-ecological zone, drought, GIS, growing period, *Oryza sativa*.

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Introduction

Rice (*Oryza sativa* L.) is the most important food crop in the Mekong region. Rice is grown in rainfed lowland, irrigated lowland, and rainfed upland conditions, but rainfed lowland cropping is the most common (Mackill *et al*. 1996; Wade *et al*. 1999). In Laos, for instance, two-thirds of the total rice-growing area and 80% of production is in the rainfed lowland environment (Schiller *et al*. 2001). Rice yield in the rainfed lowland environment in the region is constrained by the uneven distribution of rainfall in the wet season (Inthapanya *et al.* 1996). Thus, better quantification of the availability of water for rice growth is important for improving the productivity of rainfed lowland rice. In regions where rice productivity depends on field water availability, characterisation of the length of growing period (LGP) and of water stress development can provide the geographical dimensions of soil hydrological patterns for various growing environments (Inthavong *et al*. 2011*a*).

There has been little success in using LGP to define agro-climatic zones for the rainfed lowland rice ecosystem in the Mekong region. Inthavong *et al*. (2001), for example, carried out the first study on agro-ecological zoning for crop suitability in Laos; they employed the FAO (1996) approach, linking it to the geographic information system (GIS) to define the LGP zones for rainfed lowland rice. However, this FAO approach to the classification of LGP is based solely on a simple climatic model that determines the number of days when precipitation is equal to, or greater than, half the potential evapotranspiration (Chapman 2001). It may not be reliable for the rainfed lowland rice environment, as it does not take account of soil water characteristics such as water-holding capacity, field water loss through runoff, and downward and lateral water movement, all of which can have a significant impact in determining the water availability for rainfed lowland rice (Bouman *et al*. 2001; Chen *et al*. 2002; Tsubo *et al*. 2007*a*). It also does not estimate or take into account the amount of stored water carried forward from one day to the next within the season, despite the fact that there can be a long period with standing water in rice paddy fields. A recently developed soil-water balance model has overcome the limitations mentioned above, and was successfully validated with several field water determinations conducted in Savannakhet Province in central Laos (Inthavong *et al*. 2011*b*).

Previous studies from the Mekong region have reported on edaphic and climatic factors that influence field water availability for rainfed lowland rice (Tsubo *et al*. 2007*b*, 2009; Inthavong *et al*. 2011*b*). Water availability is higher with fine-textured rather than coarse-textured soil but fluctuates with rainfall throughout the growing season. Comparison of a few locations with varying soil clay content using 20 years of rainfall data showed that soil clay content has a large effect on the end of growing period (EGP), whereas large variation in the start of growing period (SGP) is mostly associated with variation in rainfall occurring at the early part of the growing season (Inthavong *et al*. 2011*a*). However, the separate effect of soil types and rainfall patterns on spatial variation in growing period is not known.

Rice crops in the region are typically cultivated in a series of paddy fields on a sloping land, i.e. a toposequence. In high toposequence positions, water losses by percolation and seepage are large, so water availability tends to be lower (Tsubo *et al.* 2006, 2007*a*; Inthavong *et al*. 2011*b*). In soils with low clay content, the trend is for increasing water availability at the lower parts of the toposequence (Samson *et al*. 2004; Boling *et al*. 2008). As a result, when growth is constrained by water availability, the rice yields are higher in the lower parts (Homma *et al*. 2003). The variation in water availability and hence yield across toposequence positions at a local level needs to be compared with the variation at a larger scale across different districts within a province so that the accuracy of GIS maps at the larger scale can be evaluated.

The objectives of this study were therefore (*i*) to map the LGP in order to conduct a spatial analysis of LGP to examine the separate effects of soil clay content and rainfall variability, and (*ii*) to compare the variation in yield reduction due to water deficit around flowering time between large-scale geographical variation (e.g. among districts within a province) and small-scale local variation at different toposequence positions.

Materials and methods

Study area

The study focussed 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). This province has the largest area of lowland rice of any province in the country, accounting for 23% of the lowland rice area (599 000 ha) in 2004. The rainfed lowlands in the province suffer chronic drought and were therefore selected for the case study.

Climate

The province is subject to a monsoonal climate, with the south-west monsoons being associated with distinct wet (May–October) and dry (November–April) seasons. August is usually the month with the highest rainfall, receiving an average of 354 mm with a range of 131–565 mm over the 20 years 1985–2004. The median annual rainfall (based on 50% cumulative probability) shows that rainfall decreases from the southern (1400 mm) and north-eastern (1400 mm) parts of the province, to the north-west (1100 mm) (Fig. 1*a*). Rice is grown mostly in the western half of the province. Seeds are generally sown in the nursery in late April–May. The mean monthly rainfall for April (i.e. before seeding) is around 25–50 mm except in the north-west, where rainfall is <25 mm, and in the central south-west, where monthly rainfall exceeds 50 mm (Fig. 1*b*). In October just before rice maturity, most of the rice-growing area has <25 mm rainfall, except in south-western areas, where the rainfall is 25–50 mm (Fig. 1*c*). Mean weekly potential evapotranspiration (PET) based on estimates using the FAO Penman–Monteith model (Allen *et al.* 1998) is 30 mm/week with a range of 24–38 mm/week during the growing period; the eastern part of the province has a slightly higher PET (33.7 mm/week) than the western part (32.8 mm/week) (Inthavong 2009).

Soil type

In the period 1996–2000, the Soil Survey and Land Classification Centre (SSLCC) of Laos collected a total of 339 soil sample profiles throughout Savannakhet Province and analysed them for soil physical and chemical properties (Phommachak and Vonghachak 1996). It is assumed here that the soil physical parameters have not changed, since the agricultural land use practice has not changed much from the time of the sampling. Soil clay content measured from these samples was used for soil water balance and subsequent GIS mapping of the LGP in this study. The samples were mainly taken from agricultural land at a sampling density of about one soil pit to every 50–100 ha. The classification of land-use types for Savannakhet Province by clay content (Table 1; original data from SSLCC 1996) shows that >80% of the total agricultural land in the province is associated with soils with a low clay content. Overall, soils with clay contents of 7–12% and 0–7% occupy 36.7% and 31.5% of the province, respectively. The geographical distribution of soils with different clay contents is illustrated in Fig. 2. Rice paddy fields in the province are mainly on soils with clay contents <12%. A large proportion of the rice fields in the north-west, central, south and south-western part of the province have clay content <7%, and overall comprise ~20% of the total agricultural land in the province.

Model description

The water balance model used in this study has been described in detail by Inthavong *et al*. (2011*a*), so only a brief description is given here. The water balance is computed for the surface layer, which consists of standing water and the topsoil layer, and then for the subsoil layer. Components of the water balance in the surface layer are rainfall (measured), PET estimated using the FAO Penman–Monteith model (Allen *et al*. 1998), downward water loss as determined from the clay content of the topsoil (Tsubo *et al*. 2007*a*), and surface runoff when the free water level exceeds the height of the bund. In the subsoil layer, the water balance comprises input water from the topsoil layer (i.e. downward water loss) and deep percolation loss, which is determined from clay content of the subsoil. When subsoil is fully saturated, the deep percolation loss plus lateral water

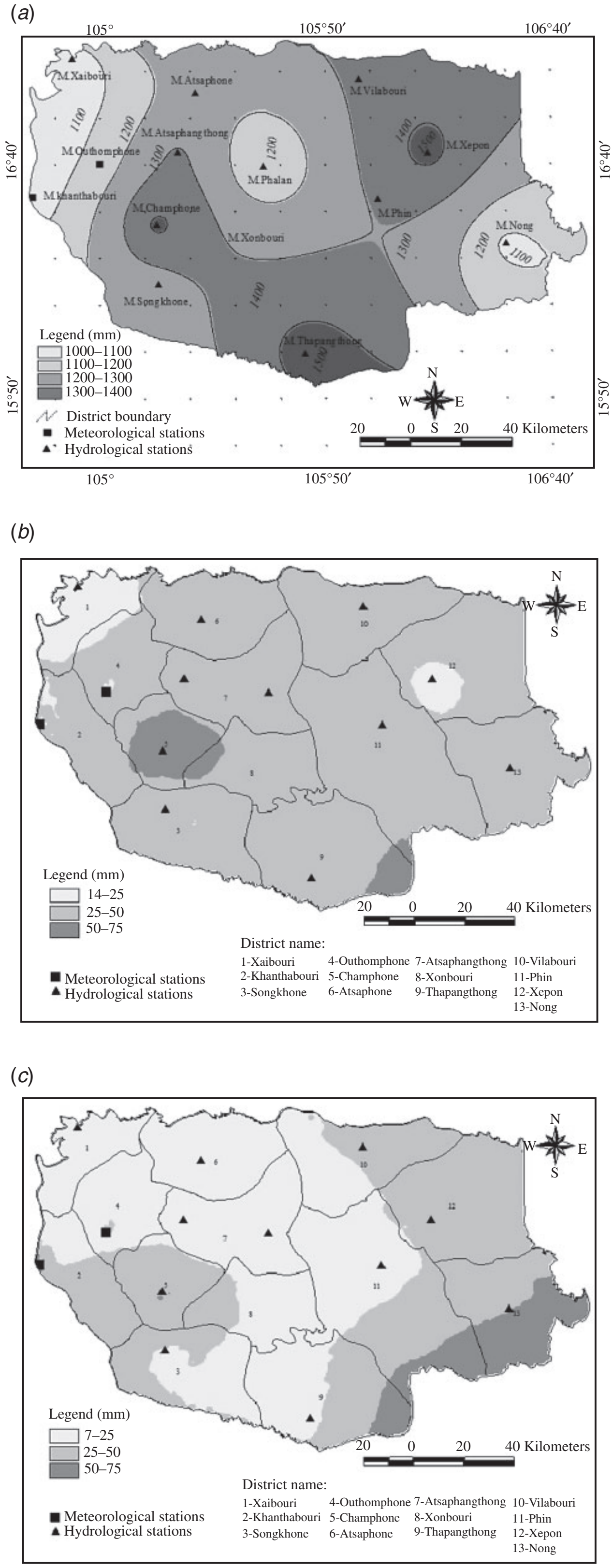

Fig. 1. Median rainfall distribution contour maps, representing 50% cumulative probability level of occurrence of rainfall event for Savannakhet Province, Laos: (*a*) annual, (*b*) April, (*c*) October.

movement from the subsoil layer is assumed to equal the downward water loss from the surface layer. The soil moisture content under air-dry condition was used as the initial soil water content of the topsoil layer at the start of a simulation run to estimate daily or weekly field water storage during the growing season (e.g. April–November).

For determining LGP, SGP was defined as the time when three continuous weeks of field water storage within the surface layer was greater than field capacity, while EGP was defined as the time when the amount of water storage within the surface layer was lower than wilting point. The LGP was then determined by the duration of the period between SGP and EGP.

Simulation procedures

Comparison of LGP with different methodologies

A comparison of two methodologies for estimating LGP, i.e. the soil water balance model and the FAO methodology (rainfall >1/2PET), was carried out by first running the water balance model with different sets of climatic inputs: (*i*) weekly rainfall for 20 individual years in the period 1985–2004, and (*ii*) weekly mean and median rainfall for the period 1985–2004. The mean of the 20 LGPs from these individual year simulations, the LGP results from the dry and wet years (2000 and 2003, respectively), and the results from using the weekly mean and median climatic inputs were then compared with estimates based on the FAO methodology using long-term mean climatic data recorded for the same period, 1985–2004. The soil parameters used were based on data obtained from rice fields in Phonsim Nua village (16°35′N, 104°53′E) in Khanthabouri district, where the soil was classified as a loamy sand with an average topsoil and subsoil clay content of 8.8% and 21.7%, respectively.

Mapping growing period

The water balance model was executed in a user-friendly spreadsheet (Microsoft® Excel using the macro programming language), coupled with raster-based GIS (ArcView GIS3.2a) running with the inputs of median weekly climate events (i.e. rainfall and PET), presenting as 50% cumulative probability level of rainfall and PET in each week, and soil water characteristics for two pathways (point-based and gridded surfaces at weekly intervals).

The model computes weekly field water storage, SGP, and EGP, and subsequently LGP at point locations by first using soil information from 339 soil profile samples obtained from the soil database for Savannakhet Province (SSLCC 1996), together with the median weekly rainfall and PET of the period 1985–2004, obtained by spatial interpolation function in GIS, namely variography and kriging (Goovaerts 1997), to generate the weekly rainfall surfaces at 5-km cell resolution for 52 weeks, using rainfall data derived from a total of 62 locations; 43 locations were within the country (33 meteorological and 10 hydrological stations), and 19 were meteorological stations in nearby north-east Thailand. Rainfall data from Vietnam near the Lao border were not included in the dataset because the rainfall pattern in Vietnam is believed to be different from Laos. This is caused by the chain of the Annamite Mountains, creating a rain shadow effect in the Lao side. In addition to this, most of the north-eastern edge of Savannakhet Province bordering Vietnam

Table 1. Classification of land use types by soil clay content in Savannakhet Province, Laos (original data from SSLCC 1996)

Clay	Agricultural land		Forestland		Grassland		Others		Total	
(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
0–7	119 444	5.8	549 000	25.7	175	0.01	6069	0.29	688 750	31.5
7–12	90 221	4.3	674 138	31.5	4538	0.21	17 488	0.82	804 062	36.7
12–20	30 132	1.5	540 769	25.3	4913	0.23	5781	0.27	595 656	27.2
20–27	3170	0.2	88 042	4.1	306	0.01	581	0.03	29 325	4.3
>27	1219	0.1	3925	0.2	–	–	156	0.01	5300	0.2
Total	244 185	11.8	185 5873	86.7	9931	0.46	30 075	1.4	214 0065	100

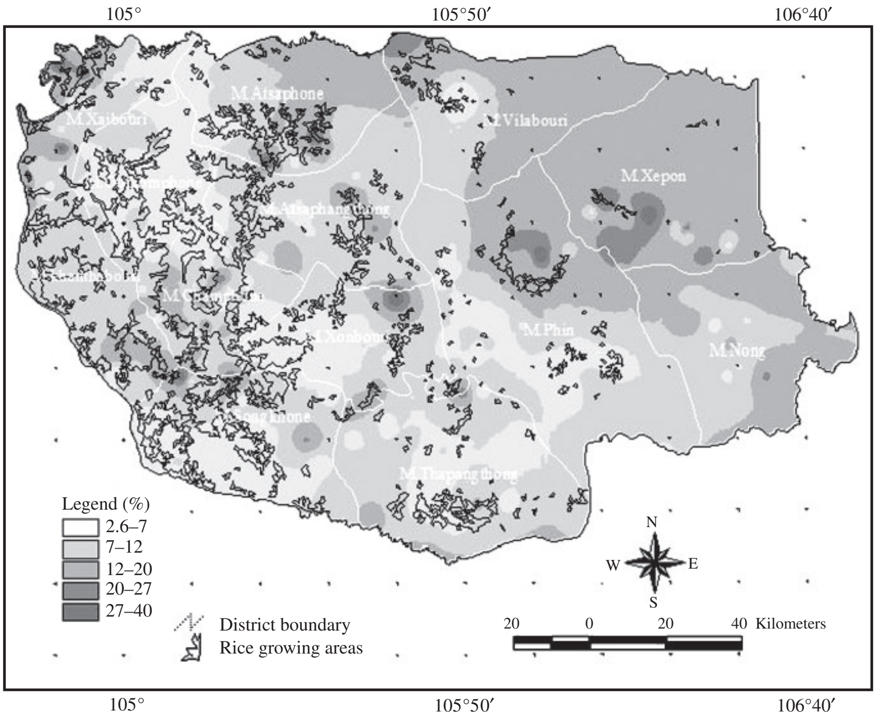

Fig. 2. Soil clay content map of Savannakhet Province, Laos (NAFRI 2000).

is not utilised for lowland rice cultivation, as the areas are mostly rolling hills with slopes >16%. The median weekly climate for PET was interpolated by using radial basis interpolation function at 22 Lao meteorological stations where all the required weather data were available for the period 2000–2004 (some stations had data for the period 1985–2004). The simulated results of LGP, SGP, and EGP at different locations were then interpolated to create gridded surface maps of LGP, SGP, and EGP for the entire province.

Estimating separate effects of soil clay content and rainfall on growing period

The water balance model was run to investigate which of the two main factors, soil type or rainfall pattern, has a greater impact on SGP and EGP and, hence, LGP. The study was conducted by using soil clay content and rainfall pattern for two analysis pathways. First, the soil-water balance model was run to compute the LGP for different soil types with contrasting clay contents, using the standard rainfall throughout the province; the aim was to determine the effect of soil clay content on LGP. For this purpose, the median weekly long-term rainfall for the whole of Savannakhet was used as a standard rainfall input. Second, to investigate the effect of rainfall on LGP, the model was run using median weekly rainfall surfaces at 5-km cell resolution for 52 weeks for the province, with the soil type kept constant using topsoil and subsoil clay contents of 12% and 25%, respectively (the mean clay contents for the whole province).

Estimating the importance of toposequence position relative to large-scale geographical variation

Yield reduction (YR) due to water deficit was estimated using a linear equation developed by Ouk *et al.* (2006): YR (%) = –1.68WL_{REL} (cm), where WL_{REL} (<0) is relative field water level (FWL) [i.e. the mean of FWL only when water condition is below the soil surface (FWL <0)] around flowering time (6 weeks, i.e. 3 weeks before and after flowering date). We used the flowering time of Lao standard cultivar TDK1 for estimation of WL_{REL}. We used this equation in two ways: one with soil water level estimated using the simulation model, and the other with measured soil water level in the field. In the first study, this equation was incorporated into the soil-water balance model using soil information obtained from 53 soil profile samples from main rice-growing areas in seven districts within the province (Atsaphangthong, Champhone, Khanthabouri, Outhomphone, Songkhone, Xaibouri, and Xonbouri), together with the 2008 gridded rainfall surface map (2008 was used as we measured soil water level at several farms, as described below) generated from rainfall data recorded at the 62 locations mentioned earlier. Once the flowering date was defined and matched with the corresponding WL_{REL}, the spatial variation in YR was estimated.

In the second study, YR was estimated using FWL data measured in farmers' paddy fields. The measurements of FWL are described in detail by Inthavong *et al*. (2011*b*), so only a brief description of the field measurements is given here. Using perforated PVC tubes with a diameter of 100–150 mm and length of 350 mm (and 5-mm-diameter holes in the bottom 100 mm), daily FWL above or below the soil surface was measured in 2008 for top, middle, and bottom toposequence positions in 45 farmers' fields across the seven districts. The number of farms in each district varied from three to 11. Considering the number of farms as replications, a two-way ANOVA with the Tukey test was conducted to examine variation in YR across districts and toposequential positions.

Results

LGP with different methodologies

The estimates of LGP using the different methodologies are summarised in Table 2. The results show some differences in SGP, EGP, and LGP with respect to the methodology used. The LGP results with the climate data for individual years indicated considerable year-to-year variability as shown for the two extreme years (2000 and 2003). However, the mean SGP, EGP, and LGP, estimated from the results of individual years, are similar to those based on the use of mean climatic data as inputs. The estimates based on the long-term means of climatic data differ from those based on individual years by only 1 week. The use of median rainfall data resulted in a 1-week delay in the start of, and a 1-week earlier finish to, the growing period, giving an overall shorter LGP by 2 weeks. When the FAO methodology was used to estimate LGP, the growing period tended to start and also end earlier than for estimates based on the soil-water balance method (Table 2). An exception to this was for the year 2000, in which high early rainfall resulted in an early start to the growing period.

Effects of soil clay content and rainfall on growing period

When SGP was estimated under standard, long-term rainfall inputs throughout the province but actual soil type (clay content), there was almost no effect of soil type on SGP, which varied between weeks 19 and 21 (i.e. in May) of the year (Fig. 3*a*). When the model was run with a standard soil type and actual rainfall data, on the other hand, SGP varied greatly, from week 19 to week 27 (Fig. 3*b*). Growing period commenced in weeks 19 and 21 in most areas, but in areas of the north-west, south-western corner, and central north, SGP was delayed by 2–4 weeks. The SGP pattern estimated from actual soil and rainfall data had the largest variation (Fig. 3*c*), and it tended to follow the pattern of SGP variation obtained under actual rainfall and standard soil type. Thus, the central south had the earliest SGP, with gradual delay towards the northern part, particularly the central north of the province, although south-western corner was also delayed in SGP.

The effect of soil type on EGP under standard rainfall throughout the province was rather large, resulting in an EGP range between weeks 39 and 47 (Fig. 4*a*). The growing period finished earlier (before week 43) in some areas in the north-west, south-west, and central south, where soils with a coarse texture (<7% clay content) predominate, relative to large areas of the west and central south-west of the province, which have soils with >7% clay content (Fig. 2). Under the standard soil type but with actual rainfall patterns, the EGP varied between weeks 43 and 47 for most rice-growing areas, with the growing period ending later in the south-west (Fig. 4*b*) where October rainfall was generally higher (Fig. 1*c*). With actual rainfall and soil type as inputs, the EGP variation (Fig. 4*c*) reflected more in variation in soil type (Fig. 2) and hence the EGP map in Fig. 4*a*, although the delaying effect of high late-season (October) rainfall in the south-west (Fig. 1*c*) can be also seen in Fig. 4*c*. Thus, EGP was before week 41 in some areas of the north-west, while most of the central part of the province had EGP between weeks 41 and 43, and some areas in the south and west between weeks 43 and 45.

Table 2. Comparisons of simulated results for the start, end, and length of growing period (SGP, EGP, and LGP, respectively) for rice planted in Phonsim Nua village (16°34′N, 104°51′E), Khanthabouli district, Savannakhet Province, Laos

	Soil-water balance method					FAO
	Single-year climate data			Long-term climate data		
	Mean from individual years[A]	Wet (2000)	Dry (2003)	Mean[B]	Median[C]	Mean[D]
SGP (week of year)	19	16	20	19	20	16
EGP (week of year)	45	45	43	46	44	42
LGP (weeks)	27	30	24	28	25	27

[A]Mean of simulated results using inputs from individual years (1985–2004).
[B]Using mean long-term climate data (1985–2004).
[C]Using median climate event (estimate based on 50% probability level of climate data 1985–2004).
[D]FAO methodology: rainfall >1/2 PET using mean climate data (1985–2004).

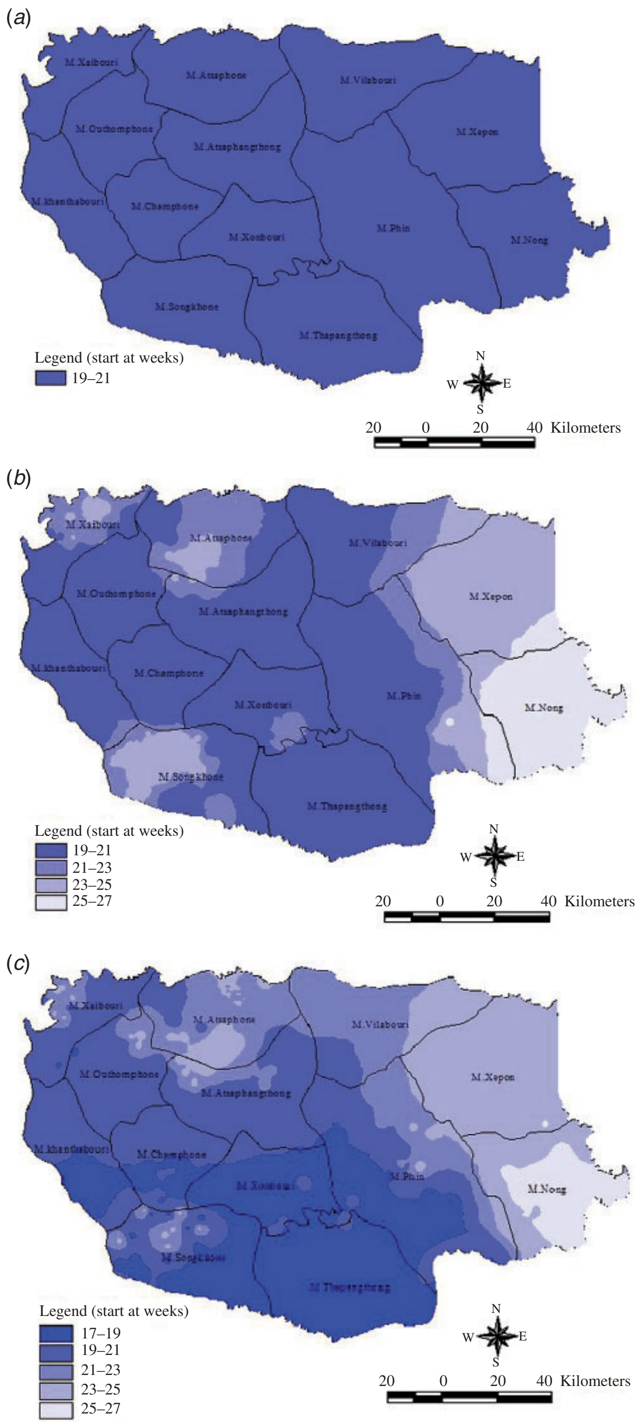

Fig. 3. Start of growing period (SGP), as estimated by the soil-water balance method using: (*a*) standard rainfall and actual soil types, (*b*) actual rainfall and standard soil type, and (*c*) actual rainfall and actual soil types, for Savannakhet Province, Laos.

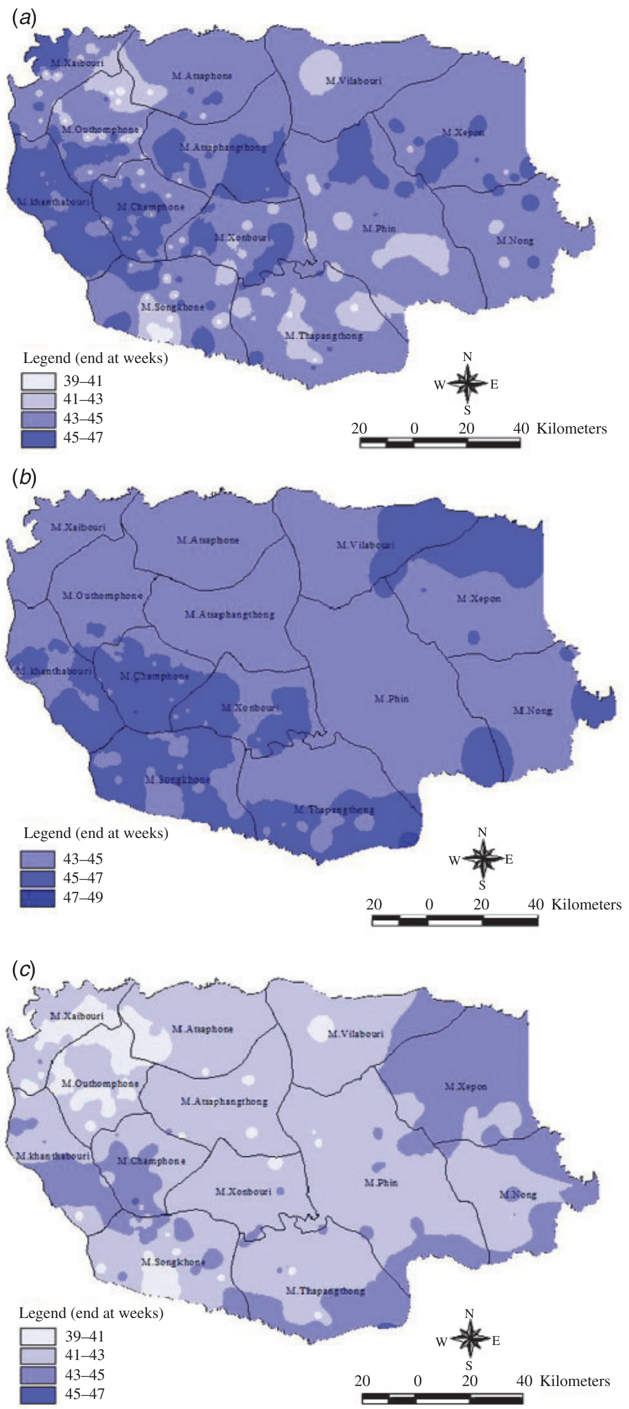

Fig. 4. End of growing period (EGP), as estimated by the soil-water balance method using: (*a*) standard rainfall and actual soil types, (*b*) actual rainfall and standard soil type, and (*c*) actual rainfall and actual soil types, for Savannakhet Province, Laos.

The effect of soil type on LGP was large, with differences of up to 10 weeks in the main rice-growing area of the province (Fig. 5*a*). As there was almost no effect of soil type on SGP, the LGP map here reflected the map of EGP in Fig. 4*a*. Rice fields on soil types with clay content <7% in the north-west and south-west had LGP of 21–25 weeks, this being considerably shorter than for other soil categories in the province. When the model was run with the standard soil type and actual rainfall, a short LGP of <21 weeks was associated with the areas in the central north and the north-western corner, while the remaining areas had

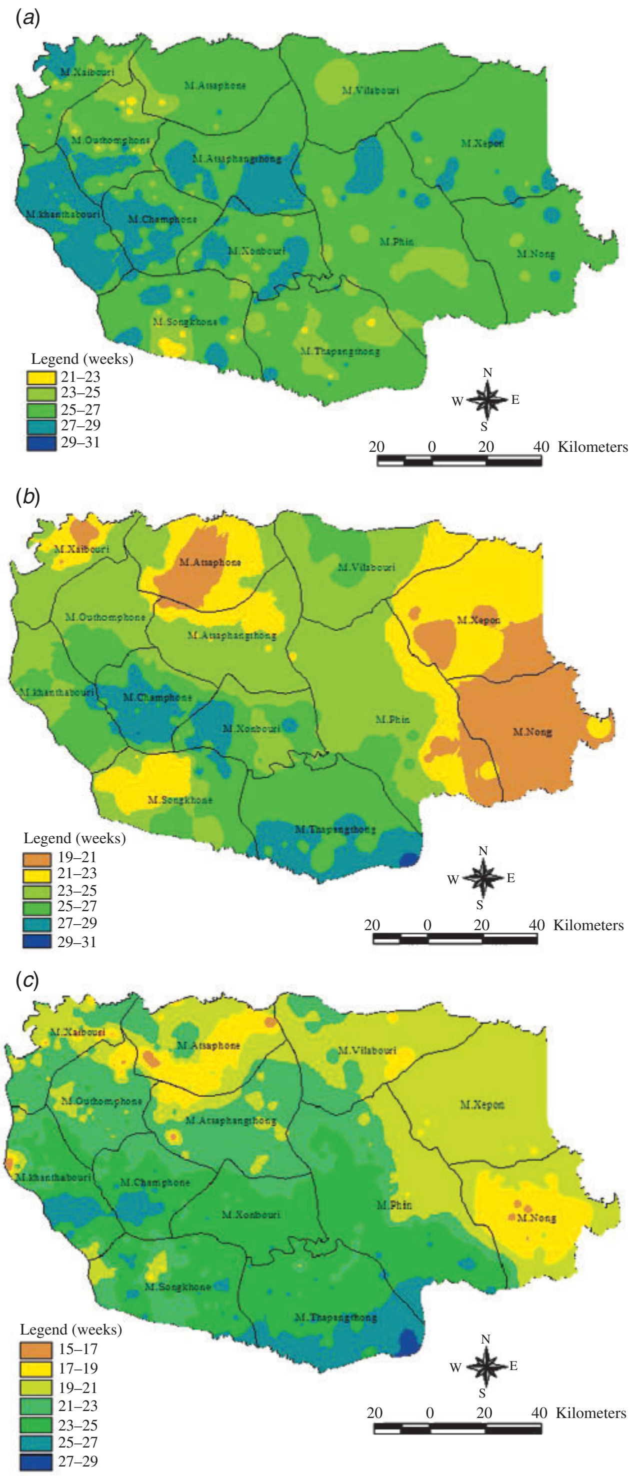

Fig. 5. Length of growing period (LGP), as estimated by the soil-water balance method using: (*a*) standard rainfall and actual soil types, (*b*) actual rainfall and standard soil type, and (*c*) actual rainfall and actual soil types, for Savannakhet Province, Laos.

intermediate LGP ranging between 21 and 25 weeks; an exception to this was in areas in the south and central south-west, which had long LGP of >25 weeks (Fig. 5*b*). With actual rainfall and soil types as inputs, variation in simulated LGP was large (Fig. 5*c*), ranging from 15 to 29 weeks. This reflected in LGP patterns determined by variations in both rainfall and clay content.

LGP zones in Savannakhet province

Based on an analysis of the above results that used median weather data available from the meteorological stations of the province, the agricultural land in the seven districts where actual water level was determined, mostly lying in central and western Savannakhet province, can be delineated into three main LGP zones (Table 3). The short LGP zone (<21 weeks) covers most of the area in Xaibouri district and one-third of the area of Atsaphangthong district. These lowland areas are likely to be subjected to lower rainfall (Fig. 1) and have soils with relatively low clay content (Fig. 2). The intermediate LGP zone (21–25 weeks) occupies almost all areas in the districts of Outhomphone and Xonbouri. Most areas of the districts of Atsaphangthong, Champhone, Khanthabouri, and Songkhone also belong to this zone, and >75% of the total area of the seven districts is classified into this zone. The long LGP zone (>25 weeks) mainly covers Champhone district, as well as the districts of Khanthabouri and Songkhone. Field water availability is favourable in this zone on account of relatively high rainfall (Fig. 1), and the soils having comparatively high clay content (Fig. 2), which enables them to hold more water and reduce the possibility of water stress at the end of the growing season.

Effect of toposequence position relative to large spatial variation

As shown in Table 4, the yield loss estimated from the water levels determined in 2008 was larger for rice fields in the districts of Outhomphone and Atsaphangthong than in the districts of Champhone and Songkhone ($P < 0.01$). Observed FWLs during flowering time were low in rice fields of Outhomphone and Atsaphangthong districts, and these are the districts where the fields tended to have relatively shorter LGP than those of Champhone and Songkhone districts (see Fig. 5*c*). At a local scale, the FWLs were generally lower at the top position of the toposequence than the middle and bottom positions, and the yield reduction was estimated to be larger for the top position in all districts, except Atsaphangthong where the yield loss was estimated to be higher at the bottom position (Table 4). Overall, crop water deficit was significantly more severe for the top position of rice fields than for the other two toposequence positions ($P < 0.01$). The variance ratio for the effect of toposequence position ($F_{2,114} = 12.87$) was higher than for the effect of district ($F_{6,114} = 9.32$), indicating that toposequence positions contributed more to the variation in yield reduction.

The simulated results of yield limited by water deficit for the 2008 rice-growing season show that the yield reduction was greater than that based on observed FWL, but that Outhomphone district encountered severe water deficit in response to late-season drought which caused simulated yield reduction of 29%, followed by Xonbouri and Atsaphangthong (Table 4). Therefore, rice yield in Outhomphone district was

Table 3. Areas (ha) for different zones of the length of growing period (LGP) (short, intermediate, and long) estimated from median rainfall of long-term data across seven districts of Savannakhet Province, Laos

Values in parentheses are the proportion of the district's area within the LGP zone

District	Location in province	Short: <21 weeks	Intermediate: 21–25 weeks	Long: >25 weeks
Atsaphangthong	Central	6856 (35%)	12 869 (65%)	–
Champhone	Central south-west	–	28 038 (63%)	16 813 (37%)
Khanthabouri	West	381 (2%)	17 344 (72%)	6300 (26%)
Outhomphone	Central north-west	944 (3%)	30 094 (97%)	–
Songkhone	South-western	2106 (5%)	31 375 (80%)	5856 (15%)
Xaibouri	North-western	13 175 (66%)	6719 (34%)	–
Xonbouri	Central	–	14 275 (92%)	1306 (8%)
Total		23 462 (12%)	140 714 (72%)	30 275 (16%)

Table 4. Yield reduction (%) estimated based on observed field water levels for rainfed lowland rice in different toposequence positions (top, middle, and bottom) in the 2008 wet season, across the main lowland rice fields in seven districts of Savannakhet province, Laos

Corresponding yield loss from simulated results for the middle toposequence position is also shown. Means followed by the same letter for different districts or for different toposequence positions are not significantly different at $P = 0.05$

District	No. of farms	Observed yield reduction				Simulated yield reduction
		Top	Middle	Bottom	Mean	Middle
Atsaphangthong	7	8.1	7.9	10.9	9.0a	17.4
Champhone	11	0.1	1.0	1.2	0.8b	0.7
Khanthabouri	4	20.3	4.5	0.0	8.3ab	5.0
Outhomphone	7	24.9	9.1	5.3	13.1a	29.0
Songkhone	7	0.0	0.0	0.7	0.2b	3.6
Xaibouri	3	14.7	0.0	0.0	4.9ab	0.0
Xonbouri	6	8.8	8.3	4.5	7.2ab	20.5
Mean		11.0a	4.4b	3.2b		10.9

estimated to be more severely affected by drought, although the district had mostly intermediate LGP.

Discussion

The results of the study (Table 2) show the usefulness of the simulation based on the use of climate data for individual years compared with those based on the use of mean climate data, because the former provides the probability of variability in LGP, SGP, and EGP across years due to rainfall variability. However, such simulation studies require long-term climate data from a large number of meteorological stations (cf. only two meteorological stations with long-term climate data available in Savannakhet Province). The simulation using mean climate data provided similar results to the mean of LGPs for individual years; however, the use of mean rainfall data may be less reliable because the occurrence of large rainfall events increases mean rainfall, but they are not effective in increasing soil water availability to the crop. Median climate input was used in most simulations in this study because, unlike the use of mean values, it can take account of an excessively high rainfall event. The concept of reliable rainfall was also introduced by Kam *et al.* (2000); they defined annual rainfall with a probability level >0.75 as realistic rainfall in determining the humid period for the growing season for rainfed lowland rice.

The present study shows that the FAO approach estimated SGP and EGP to be earlier in the season for the typical lowland condition than the water balance simulation approach (Table 2). Similarly, for all lowland rice-growing areas in Savannakhet Province, Inthavong (2009) produced SGP, EGP, and LGP maps based on the FAO approach, showing a growing period which started earlier (between weeks 15 and 17) than that based on the soil-water balance method used in the current study (between weeks 17 and 27). A comparison of the two approaches also shows lower variation in EGP (between weeks 41 and 42) using the FAO approach compared with the soil-water balance method (between weeks 39 and 47), and long LGP (>25 weeks) using the FAO approach compared with the current study (Fig. 5*c*, mostly <25 weeks). Thus, different LGP results were obtained with the different methodologies, as the FAO methodology and the soil-water balance method have differing criteria for defining LGP. However, as the soil parameter (clay content) is an important factor in the determination of moisture availability for lowland paddies (Tsubo *et al*. 2007*a*) through its effect on downward water and deep percolation losses, the LGP estimates based on the soil-water balance method would be more accurate than the estimate based only on rainfall and PET (i.e. the FAO methodology).

Although rainfall has a large influence on field water stored, short LGP and an early finish of the growing season are also associated with low soil clay content in the area covered by the study. The shortest LGP was mostly associated with soils of low clay content and intermediate rainfall in the central north-west (Outhomphone district) of the province (Fig. 5*c*). The area with the shortest LGP in the central north-west is known to have a severe problem with drought, and low yields of <2 t/ha are common for rice crops grown on the coarse-textured soil in the fields (Manivong and Douangsavanh 2007). This contrasts with the high clay soil of rice fields in the central west (Khanthabouri district), which have long LGP and where high yields of >2 t/ha are recorded, even though these areas received similar rainfalls (Fig. 1*a*). Özdemir *et al*. (2000) also reported that the soil clay content was the most important soil property to influence water retention, as the clay particles play an important role in the adsorption and desorption of water molecules. In addition to the edaphic effect on LGP (and also EGP), late SGP is associated with low rainfall, particularly at the beginning of the wet season (Figs 1 and 3). Thus, areas with late SGP are considered to be those prone to early drought. Similarly, early EGP areas can be considered as those prone to late drought, and these areas can utilise quick-maturing varieties to escape the late-season drought (Fukai *et al*. 1999).

Areas with shorter LGP, e.g. Atsaphangthong district, are associated with greater yield loss (Table 4), resulting mostly from low clay, coarse-textured soils, and thus low field water availability. In contrast, the yield was not reduced in the areas with a longer LGP, e.g. Champhone district, because of potentially high water availability within a growing period. Thus, there is general agreement between LGP and estimated yield loss due to drought during the growing period based on field observation of water level. However, Outhomphone district, which had mostly an intermediate growing period (21–25 weeks) (see Fig. 5*c*), had a large yield reduction according to the 2008 growing condition (Table 4). This indicates that the characterisation of drought environment should not rely solely on the estimation of LGP. The present study further revealed that the variability of yield loss within a small catchment could be larger than the regional variation. This confirms the importance of characterising water environment on sloping land for rainfed lowland rice (Jongdee *et al*. 2006). While the current model is useful in estimating LGP and water deficit development within the cropping season at a large scale such as district level, the present study has shown that the model may need to be improved to cope with the large variation in water availability, and hence yield, within a sloping land within a relatively small area. This aspect could be modelled by estimating lateral water flow for different toposequence positions.

The approach taken in this study has shown factors that determine the length of growing season and drought environment. The maps produced are useful in identifying areas that are prone to drought. Thus, in the case study here, the Savannakhet Province can be delineated into three main LGP zones: a short LGP zone was defined in the central north-west, an intermediate zone was defined for most areas of the province, and a long LGP zone was defined for the south-western and western parts of the province. Crop management practices including variety selection may be adjusted according to these zones with different LGPs. Agricultural extension officers in each district may recommend appropriate crop management practices. Further, in some districts where the map indicates favourable growing environments but where rice may not be currently grown on a large scale, preliminary investigation may be made to cultivate rice. This present approach of combining the use of simulation model and GIS mapping has been extended to develop drought maps for other provinces in Laos, and then further to neighbouring Thailand and Cambodia.

Conclusion

The zoning maps of LGP, SGP, and EGP for rainfed lowland rice in Savannakhet Province were developed using a soil-water balance model run with the inputs of median weekly climatic data and soil water characteristics. The simulated LGP results based on the soil-water balance model were found to be superior to the FAO approach. Declining rainfall from the southern and south-eastern parts to the north-western corner of the province, and soil types with varying clay content, contributed to the classification of the LGP zones. Although clay content in soils and rainfall distribution pattern are both important factors influencing LGP, spatial variation in the SGP was due more to timing of initial wet season, while spatial variation in EGP was strongly dependent on soil clay content. The LGP zone maps can provide a geographical dimension of soil hydrological patterns for various rice-growing environments and also identify the spatial pattern of drought stress that is likely to occur. These LGP maps can be used to provide guidelines for determination of appropriate crop management strategies (e.g. time of planting, varieties). Also, quick-maturing, drought-tolerant varieties need to be developed to avoid late-season drought in areas with low clay content soils and in high toposequence positions (Fukai and Cooper 1995; Jongdee *et al*. 2006; Ouk *et al*. 2007). Therefore, the information generated in this simulation study is potentially useful for the formulation of strategies for the rice breeding program.

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