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Intensifying rice-fallow systems in Southeast and South Asia with grain legumes and/or dry season crops: analysis using field experiment and simulation

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Contents

I. General introduction

1. Lowland rice-based cropping systems in Southeast and South Asia

Rice is one of the most important cereals in the world and the most common staple food of many Asian people. It is grown in various environments and mostly under irrigated and rainfed conditions. Irrigated rice is generally grown in bunded fields with fortified irrigation during one or more crops growing season. Rainfed rice is typically grown in the fields that are flooded with rainwater for at least part of the growing season with the depth of water highly variable (GiRSP, 2013).

The majority (~75%) of the world's rice production is provided from irrigated rice fields with about 40 to 46% of such areas located in Asia. Of the 52 million ha of rainfed lowland rice worldwide, around 46 million ha are in Southeast and South Asia (IRRI, 1993). In irrigated fields, rice is mostly grown in a monoculture system with 2-3 crops per year. However, in some areas, rice is grown in rotation with another crop such as wheat (Ladha et al., 2003; Dawe et al., 2004), maize (Bijay-Singh et al., 2008) or legumes, with the later mostly practiced by farmers in Indonesia, Philippines, Myanmar, Vietnam, Bangladesh and Southern Bangladesh (George et al., 1992).

In rainfed fields, rice is grown in a flooded system prior to and during crop growth. As rainfall as the main source of water in this system, lack of water control becomes a main problem which in turn can lead to flooding and drought. Because of rainfall pattern, only single rice crop per year is normally practiced by farmers (Garrity and Liboon, 1995). It is possible to grow a second rice crop after rainy season if additional irrigation is available during the crop growth stage. However, the success of a second rice crop is often limited due to less water availability. Farmers therefore cultivate dry season crops such as legumes that require less water compared to rice crop so as they can obtain additional income to assist their families (Buresh and De Datta 1991; Kirchhof et al., 2000). In many areas however, fields are often left fallow after the rice harvest due to insufficient water supply and the adversity in land preparation induced by poor soil physical conditions (Garrity and Liboon, 1995, ; Gumma et al 2016; Ladha et al., 1996). This fallow phase conditions causes the lands idle during the dry season; hence farmers cannot obtain any additional income during this season.

Rice soils rely upon interchangeably wet and dry seasonal cycle. During land preparation and at least part of rice growing season, soils are typically flooded and anaerobic. On the other hand, when soils are cultivated with dry season crops, soils are not flooded and aerobic (Singh et al., 2005). Since soils are generally plowed, puddled and kept flooded over rice growing season, soil structure is destroyed and organic matter decreases, thus providing low soil productivity for the following crops (De Datta and Hundal, 1983; Timsina and Connor, 2001). On flooded soils, the movement of oxygen in the water is slower than in the air, the supply of oxygen from the air cannot fulfill the oxygen demand of aerobic organisms in the soil, therefore microbial and biochemical processes in the soils are changed, inducing a reduction in the oxidation-reduction potential. Hence, anaerobic metabolites such as volatile fatty acids, CH_4 and sulfide, and ammonium (NH_4-N) accumulate in reduced soils crucial for growing a rice crop (Watanabe, 1983; De Datta, 1995). Conversley, under aerobic conditions, NH_4-N is oxidized to NOs that can be utilized by crops or leached (Buresh and De Datta, 1991; George et al., 1992).

The alteration of anaerobic and aerobic conditions affects microbial carbon (C) and nitrogen (N) dynamics (Fierer and Schimel, 2002) as well as enhances inorganic N, especially during anaerobic conditions (Watanabe, 1983). Since the crop cannot take up the excess of mineral N, the excess may be lost through denitrification or leaching (Buresh and De Datta, 1991; Qiu and McComb, 1996).

2. Legumes in lowland rice-based cropping systems

Legumes are the most common dry season crops in lowland rice-based cropping systems, and are grown during the dry period after rice under rainfed conditions and depend on the stored water in the soil profile (Buresh and De Datta 1991). These crops can be grown either preceding or following rice depending on water availability, and are a potential source of food, animal feed, fodder and green manure. Moreover, legumes are likely to affect the soil N capacity for the following crops by providing N and C in the soil (Moore, 2000) and may also reduce nitrate (NO_3-N) leaching to deeper soil layers beyond root zone (Singh, V.K et al., 2005). Therefore, the inclusion of legumes into these systems not only provides the opportunity to enhance and sustain productivity, but also improves income of farmers (Buresh and De Datta 1991; Chandrasekaran et al. 1996).

Soybean, mungbean, peanut and cowpea are the main legume crops cultivated on rice field in Asia (Buresh and De Datta 1991). Mungbean is a popular dry season crop grown after rice in Indonesia and Philippines. Farmers prefer to grow mungbean compared to other legumes due to its lower requirement for water, short growing period and relative tolerance to waterlogging (Rahmianaa, 2007). Yields of mungbean, however, are low and usually <1 t ha^{-1} in Indonesia (Radjit 1994) and ranging from 0.3 to 0.8 t ha^{-1} in the Philippines (Sanidad 1996). Low inputs and poor crop stand management become a major cause of low yields. Soybean is the major dry season crop in Thailand with about 1.8 t ha^{-1} of yield and 190,000 ton of total production being harvested in 2013. Soybean is also the most common grain legume grown in Indonesia with about 1.6 t ha^{-1} of yield and 779,992 ton of total production being harvested in the same year (http://faostat.fao.org/site/567/DesktopDefault.aspx). This yield is low compared to the potential yield of about 2.7 t ha^{-1} (Sumarno and Adisarwanto 1992). Furthermore, low yields are influenced by factors such as poor crop stand, excessive water at planting, and poor contact between seed and soil.

Legumes are typically planted when soil is still wet and occasionally under puddled and saturated conditions. In these conditions, seedlings can be damaged due to waterlogging, and when the soil puddled dries out, soil strength is quickly increased. As a consequence, the emergence and growth of root become inhibited, causing poor crop establishment and performance (Kirchhof et al., 2000). Even when crops are planted under sufficient soil water content, they may endure drought stress during the later stages of their growth leading to increased risk of crop failure (Buresh and De Datta 1991). Therefore, sowing time is important for the success of legumes in lowland rice-based cropping systems. Interaction between crop growth and environmental conditions will determine the favorable window for sowing.

Tillage is commonly practiced by farmers to improve soil physical conditions, but it is costly, time consuming and reduce residual soil moisture (Zandstra, 1982). Zero tillage therefore is applied to get benefit of soil residual moisture which in turn provides good soil water and aeration conditions, resulting in higher germination. In addition, zero tillage may help to conserve soil moisture thus minimizing crop failure in the later stages of crop growth and to reduce labour use in preparation of land (Nizami, 1991). However, when water is sufficient to irrigate legumes throughout their growing season such as in irrigated rice fields, intensive tillage is usually recommended.

3. Climate related to lowland rice-based cropping systems

Lowland rice-based cropping systems also deal with another constraint related to climate conditions. In tropical regions, the primary climate variable that greatly affects the diversity of crop production is precipitation either due to its high variability in time or location (Boer, 2002). During periods of insufficient rainfall, crops are easily affected by heat stress, while during periods of excessive rainfall, crops may be affected by waterlogging stress. Under heat stress, carbon assimilation of crop is reduced through stomatal closure, onward modifying biomass partitioning to the different crop components. On the other hand, during waterlogging periods, oxygen content in the rooting zone is decreased, causing a decrease in root activities, an increase in root senescence and root death rates. As a consequence, water uptake is reduced, thus interfering crop growth and development (Hoogenboom, 2000). Other climate variables associated with crop production are air temperature and solar radiation. In general, an increase in temperature causes an increase in the rate of development. However, at extremely high temperatures, the developmental rates slow down as temperature increases. Solar radiation plays a crucial role as a source of energy for photosynthesis, influencing carbohydrate and biomass partitioning of crop components (Boote and Loomis, 1991). Furthermore, areas with high radiation and adequate water availability have a high-level of crop productivity.

Climate in most Southeast and South Asian countries is dominated by the monsoon (seasonal shift in wind) circulation. In line with that, Lal et al. (1998) stated that around 60% of areas in India planted to crops correspond to the southwest monsoon season, indicating its heavy dependence on the monsoon rainfall. The position of a country, the topography shape and the disturbance of tropical cyclone are also expected to take effect on climate variability (Boer, 2002).

In addition, the phase of El Nino Southern Oscillation (ENSO), the result of a two-way interaction between the ocean and the atmosphere in the tropical Pacific Ocean, is more likely to occur. ENSO is the dominant sources of climate variability on inter-annual range in many parts of the world (Tranberth & Caron, 2000). The ENSO phenomenon will disrupt the global atmospheric circulation.Consequently, a drastic decline in rainfall amount sometimes associated with El Nino events or excessive rainfall sometimes associated with La Nina may led to the prolong drought or waterlogging, respectively. Las et al. (2008) specified that extreme weather events, especially El Nino or La Nina, result in the failure of crops, which leads to the decrease of planting index and hence reduces productivity and production, damages agricultural land resources, increases the frequency and intensity of drought, increases humidity and increases the intensity of plant pests disturbances.

To intensify the productivity of dry season crops, appropriate management practices are required that enable the crops to grow more reliably and productively. However, information on how to reduce the risk of crops related to the impact of climatic variation are limited, particularly concerning sequences of rice and dry season crops as stable and sustainable lowland rice-based cropping systems. Therefore, an approach is required to improve understanding of the impact of climatic variation, which allows farmers to respond to climatic variability and possible future climate change.

4. Seasonal climate forecasts

One way to enable the better management of crop production under highly variable or changing climates is through the use of seasonal climate forecasts (SCF) for responsive management. Seasonal climate forecasts are a form of information that has economic value when they allow people or institutions to improve their utility from the level they would expect without the forecasts (Hill and Mjelde, 2002). This information such as the onset of the rainy season, the probability of rainfall occurrence or long dry spells, enables farmers to better tailor management decisions to the next weather conditions in dealing with either the advantage of favorable or the adverse conditions (Hansen, 2006). Amien (2004) described that information on SCF in agriculture can be not only useful in providing planting or spraying decisions, which is used by extension services, but also integrating into early warning alerts associated to food security. In addition, it can be used to evaluate risk and to gauge possibility related with the variability.

To effectively use the information, SCF's have to comprise a need that is real and perceived, be able to provide an understanding of decision options and tailor with the decision maker and constraints. In addition, prediction of climate variability components has to be in a relevant period, at a proper scale with adequate skills and and be timely for taking relevant decisions. Other requirements for streamlined use of SCF are the audience who receive the information has to be the right audience, so thus they can correctly interpret the information at the right time and create in a form that can be applied in decisions problems. Eventually, the operational use of forecasts has to be sustained, involves institutional commitment in providing information and supporting its application to decision making as well as policies that promote beneficial use of SCF (Hansen, 2006).

In most countries, information on SCF's are provided by national meteorological services (NMS), agency of the national oceanic and atmospheric administration, which is responsible for providing weather, climate, hydrology, forecasts and warnings. The NMS have established valuable long historical records by performing observation and monitoring networks (Amien, 2004). Similarly, in agriculture sector, NMS must timely allocate accurate information on agrometeorology. Research and education require specified information on variables with strong influence on crop growth and farm management such as precipitation, daily temperature, solar radiation, and wind speed. Meanwhile, agricultural policy makers, planners and institutional support systems require general information such as monthly rainfall and temperature along with spatial and temporal climate variability.

Several studies have been done to get better understanding on SCF, indicating that the skills on climate forecast is important. As stated by Hammer et al. (1996), a skillful SCF allows farmers to increase the preparedness on the uncertainty of climate variability by reducing the spread of possible output for the forthcoming season relative to the distribution of climate and by carrying shifts in the central of climate output. In accordance with that statement, Amien (2004) found that seasonal forecasting could provide useful guidance to agricultural communities by informing them of expected weather conditions in time to schedule farming operations such as plowing, planting, irrigating, spraying, and harvesting or to enable pre-emptive action to reduce losses from drought, flood, or other extreme weather phenomena. Besides, a clear picture of what is likely to happen in the future would provide policy-makers and planners with information, hereinafter to formulate strategy to overcome with El Nino events and climate change (Amien et al., 1999).

5. Methodology

5.1 Data acquisition and analysis

Data acquisition is the process of collecting and recording fundamental experimental information (Navar, 2010). Good data acquisition and record keeping is crucial for experimental science and technology to supply basic information for further analysis and generalization.

Data obtained by other researchers is collected and used as new data for analysis. The new data received is analysed in computational simulation. Furthermore, data is evaluated and compared.

5.2 Farm survey

Smallholder farming is easily affected by climate variability and dealt with the risk caused by climate change. An increase of rainfall and flooding or drought events due to climate change may influence the activity and productivity of smallholder farmers (IPCC, 2007). To cope with climate risk and to adapt to future climate change, they need to improve their management cropping systems (Muller et al., 2001). SCF‘s therefore provide information to define strategies to reduce climate risk during crop growing seasons.

Survey on local farmers devise how seasonal forecast could be used in managing rice and dry season crops. Questionnaire on how farmers risk management practices includes how to come in contact with farmers, how many farmers, location of the survey, kind of method, random selection or structured, gender aspects, social economic conditions, the process of decision making generally practiced in the field, and the capacity and habit on climate forecast related to risk management practices is prepared.

5.3 Crop simulation model

To quantify better transformation of climate information, agrometeorological data is able to be further analyzed by defining their effect on crop performance and comprehending the interaction between crops, soil, weather and management (Amien, 2004). For that purpose, developing techniques of modelling or simulation such as model prediction could be used in the system. As stated by Hoogenboom (2000), crop simulation models are a tool to estimate agricultural production as a function of weather, soil conditions as well as crop management. Correspondingly, Amien (2004) indicated that simulation models are the ideal instrument to implement the analyses. However, before the models can be used, they must be tested and validated in different places. This step requires a good dataset of all variables involved, including agrometeorological and soil data, crop data such as phenology and management that has been applied.

Many field studies showed that management practices such as planting time adjustment, water management, and tillage can be used to increase legume production, nevertheless they are time consuming and expensive. In addition, these studies are mostly conducted at a small plot scale in the fields, but results are projected to the whole area. Recommendations then may not take into account the variability of soil and climate across various sites within an area (Matthew et al., 2000). Simulation studies could therefore be useful to interpret the interaction between soil, crops, management options and weather in lowland rice-based cropping systems. Modeling is able to explain the correlation among the components of complex systems, give more insight into processes and verify the consequences of management as well as explore the potential for modification. Besides, it is able to integrate a lot of information from various experiments at various sites and manage to extrapolate the information to another region of interest under various soil and climatic conditions (Matthew et al., 2000).

The APSIM model represents a versatile software system for simulating the production and environmental consequences of agricultural production system (Holzworth et al., 2014). APSIM has the ability to simulate a range of crop and soil process, in response to management options that include crop sequences and species mixtures. Furthermore, APSIM was developed to simulate biophysical process in farming system, in particular where there is interest in the economic and ecological outcomes of management practice in the face of climatic risk (Keating et al., 2003). In line with that, APSIM was developed primarily as a research tool to investigate on-farm management practices especially where outcomes are affected by variable climatic condition (Holzworth et al., 2006). Numbers of simulation modeling studies have been carried out using APSIM in modeling the performance of diverse cropping systems and rotation (Carberry et al., 1996; Probert et al., 1998; Zhang et al., 2004).

Because the APSIM is firstly developed for dryland cropping systems rather than lowland rice cropping systems, the ORYZA2000 rice model, which was developed by IRRI and Wageningen University (Bouman et al., 2001), was incorporated into the APSIM framework and has been validated in some studies (Zhang et al., 2004; Gaydon et al., 2012). ORYZA2000 has become one of the most widely used and tested simulation models for rice. However, the ORYZA2000 model is tailored for rice crop in single growing season and cannot simulate crop sequence that may include rice under any cropping system. Thus, the APSIM-ORYZA can be used to simulate rice growth and development dealing with N dynamics, crop sequence, intercropping, and crop residue management as well as soil management (Zhang et al., 2004). Other models such as the CERES-Rice model are able to simulate performance of single rice crops, but it has not so far been applied to simulating long-term crop sequences or soil organic C dynamics (Timsina and Humphreys, 2006). The RIWER model for example is limited to crop species and sequences in simulating complex rice based cropping systems (Jing et al., 2010). Improvement of the existing APSIM framework enable the APSIM-ORYZA to simulate diverse environments in rice based cropping systems, particularly concerning cropping sequences involve rice (Gaydon et al., 2012). Besides, the APSIM-ORYZA has the capacity to identify not only the impacts of future climate, but also the adaptation in response to changes in rice based cropping systems.

6. Research hypotheses

The research hypotheses proposed for this study are as follows:

- In lowland rice-based cropping systems of Southeast and South Asia, successfully intensifying the system with rainfed post-rice crops is determined by crop selection, post-rice soil conditions including residual soil water and rainfall.
- Understanding historical climate patterns and applying seasonal forecasting for responsive management will enable farmers to better manage lowland rice-based cropping systems.
- Well validated crop simulation models can be used to identify the potential of legumes and/or dry season crops performance over a range of environmental and management conditions.

7. Research objectives

The objectives of this PhD thesis are:

- To specify the potential of legumes and/or dry season crops performance at range of environmental and management conditions in 3 lowland rice-based cropping systems in Southeast and South Asia.
- To examine the long-term potential of intensified rice/or fallows in relation to historical climate data.
- To calibrate and validate a farming system model that can be used to simulate legumes and/or dry season crops performance in the above-mentioned lowland rice-based cropping systems.
- To identify factors affecting farmers using climate forecast and their perceptions of climate variability and change in lowland rice-based cropping farming systems.

8. Structure of the PhD thesis

The thesis is divided into six chapters. A brief summary of each chapter is described as follows:

Chapter I:

The first chapter presents of a brief outline of the scientific background and the overall research hypotheses and objectives of the thesis.

Chapter II:

The second chapter describes the use of climate forecast in managing rice farming system in Jakenan, Central Java, Indonesia and was based on face to face interviews with smallholder farmers, using a semi-structured questionnaire that consists of open and closed questions. The interview was conducted in four villages in Jakenan sub-district and a total of 100 farmers were selected randomly based on lists of farmers available in each village. The findings revealed characteristics of the respondents, crop management that are commonly practiced in the field, and farmers' perception on climate variability and change as well as farmer's knowledge about climate forecast.

Chapter III:

The third chapter presents a simulation study on the opportunity of legumes performance at range of management practices under diverse agro-climatic conditions in Central Java, Indonesia. The APSIM model is used to assess yield for different sowing times, residue treatments, soil type and initial water levels at four sites across Central Java, Indonesia.

Chapter IV:

The fourth chapter uses field data from an experiment conducted at the Ubon Ratchathani Rice Research Centre in northeast Thailand to evaluate the potential of pre and/or post legumes crops in a rainfed rice system. The long-term potential of intensified rice/or fallows in relation to historical data and the potential of legume performance is analysed using a validated crop model APSIM.

Chapter V:

The fifth chapter uses field data from published sources from the IGP India, Tamil Nadu and Bangladesh to identify intensification option in rice-based cropping system improving productivity with non-rice crop during fallow across agro-climatic conditions. The long-term productivity of intensification options in relation to historical data and the potential of rotations improving productivity of rice-based cropping system is analysed using a validated crop model APSIM.

Chapter VI:

The sixth chapter presents general conclusions, suggests future research direction and the research results and conclusion from this study are discussed against the overall research objectives.

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II. The use of climate forecast in managing lowland rice-based cropping system in Jakenan, Central Java, Indonesia

1. Introduction

Indonesia is vulnerable to climate change, particularly since it is an archipelago country located in the equatorial region. This position makes Indonesia as a meeting point of the meridional circulation (Hadley) and the zonal circulation (Walker); both of circulations have strong influence on climate variability (Boer, 2002). The position of the sun moves from a northern to southern latitude throughout the year and the monsoon activity also plays a role in climate variability. Besides that, a very diverse topography of Indonesian archipelago affects the local agitation system that poses climate variability.

Lowland rice-based cropping systems as the main farming system in Indonesia are closely affected by changes in climatic variables such as rainfall and temperature. These systems are highly vulnerable to changes in rainfall pattern, due to the fact that the crops are seasonal and sensitive to water stress (Las et al., 2008). The rainfall has great influence in determining rice growth and production because its high variability both in time and place, while other variables have relatively small variability (Boer, 2002).

One of the factors that strongly influences rainfall variability is the phase of the El Nino Southern Oscillation (ENSO) phenomenon, which is more likely to occur along with an increase in climate variability. The ENSO phenomenon will disrupt the circulation of Walker, a circulation that is caused by the power of pressure gradient between a high pressure system over the eastern Pacific Ocean and a low pressure system over Indonesia. When the Walker circulation becomes weak, the surface of ocean is warmer than average due to upwelling of cold water occurs less, resulting El Nino. Whereas, a strong Walker circulation causes ocean temperature to be cooler than the average due to increased upwelling, resulting La Nina. Consequently, a drastic decline in rainfall amount sometimes associated with El Nino events or excessive rainfall sometimes associated with La Nina may lead to prolonged drought or waterlogging, respectively (Boer, 2002). The influence of ENSO on rainfall events has been especially significant for the dry season (Boer and Faqih, 2003). Changes in rainfall patterns and intensity due to ENSO might cause an increase in drought of rice-cultivated areas and therefore a decline in rice production. In Central Java, El Nino effects of 1994 were more pronounced than those of 1991. In 1991, although the harvested of four areas were slightly increased for the first crop, the total harvest that year decreased by almost 5000 ha. Meanwhile, in 1994, the harvested of four areas decreased four times more for the first crop compared to the total harvest that year. In 1992 and 1995, the area reduction for the first crop pointed towards further decreases in harvest area that occurred after El Nino (Amin and Las, 2000). Based on dry season rainfall data for the past100 years, a decrease in rainfall below normal due to El Nino may reach 80 mm per month, while an increase of rainfall above normal due to La Nina may be less than 40 mm per month. This indicates that El Nino pose a more serious threat than La Nina events (Boer, 2002).

Smallholder farmers are among the most vulnerable groups to be most affected by climate change (Easterling et al., 2007). The IPCC (2007) indicates that the activity and productivity of smallholder farmers can be influenced by yield reduction as crop damage and crop failure, and/or the increase of rainfall and flooding that results in waterlogging of soils. Studies show that smallholder farming in many regions is influenced by climate variability and dealt with the risk induced by climate change (Molua, 2002; Estinigtyas et al., 2012; Harvey et al., 2014; Wood et al., 2014). In line with that, climate change models mostly predict that small farmers will bear the damage, especially in rainfed farming systems in developing countries (Altieri and Koofhafkan, 2008).

Like most Indonesian provinces on Java Island, Central Java predominantly implements a rice-based cropping system. In these cropping systems, farmers generally plant two or more rice crops a year. The first rice crops are planted during the wet season, while the second and third rice crops are planted during the dry season. In addition, many farmers include dry season crops such as maize and legumes as the third crops. The impact of climate change is being experienced by smallholder farmers in this area and will continue to pose a threat in the future as climate variability increases. An increase in droughts, heavy rainfall and flooding events will cause not only crop damage through crop failure, but also reduce crop yield and threaten food security. Besides, the nutritional quality of crops will also be affected, resulting in lower protein and micro-nutrients, iron and zinc contents (IPCC, 2001).

As smallholder farmers rely on the rice-based cropping system for their livelihoods, they need to enhance their management of current climate variability that will help to cope with climate risk and to adapt to future climate change (Muller et al., 2011). One factor that may work as an advantage for farmers is benefitting from climate forecast in farming practices. The knowledge and skills of farmers regarding climate phenomena and rainfall will assist them in optimizing the use of rainfall in each season, so that they can increase crop production and forecast extreme events over the season. In addition to that, the right time of crops planting can be determined by the onset forecast that will help the farmers to prevent false rain. This information can also be used to define strategies to prevent drought risk during dry cropping season (Naylor et al., 2007). Climate forecast information therefore has to be reliable and can be used effectively by the farmers (Boer et al., 2008).

Climate information is regularly disseminated by the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) to Indonesian governmental departments, businesses and citizens (Boer et al., 2003). This information is based on the Standardized Precipitation Index (SPI) method, which has been provided by Australia, using Seasonal Climate Outlooks for Pacific Island Countries (SCOPIC) software. SPI is an index that is computed based on the probability of the recorded rainfall amount throughout every region in Indonesia (i.e. positive index values for wet, and negative for drought conditions), and can be used to observe climate conditions at various intervals, such as monthly, quarterly, seasonal, annual (Tarrant, 2014). For agricultural purposes, climate information is coordinated and served by the Ministry of Agriculture, the National Center for Agricultural Extension Development. At an operational level, district agricultural extension workers and the Regional Disaster Management Agency (BPBD) deliver climate information to the farmers.

There are several regular outputs of such climate services, such as helping farmers plan their crop management with crop calendars and variety selections. These products include forecast of rainy and dry season onset; forecast of monthly rainfall (up to three months lead time); return period map of maximum rainfall; climatology of rainfall, temperature, wind; climatology of rainy and dry season onset; maps of shifts of rainy and dry season onset; vulnerability map to drought for rice producing provinces; and Climate Field School (CFS) for farmers in crop producing provinces (Sopaheluwakan, 2011). Since rice crops are generally planted in an annual cycle, the risk factors for a second rice crop are bigger. Drought is then a dominant factor in decision making, as it is one of the main factor that leads to crop failures. Widespread drought areas are highly linked to the ENSO phenomenon and changes in sea surface temperature (SST). During El Nino years, dry season rainfall will decrease and irrigation water will be very limited, thus it cannot irrigate all the fields. Subsequently, the onset of rainy season is often delayed, by as much as three months. Planting of the first crop will therefore be delayed and this eventually also delays the second crop (Boer and Setyadipraktito, 2003).

Observation data from 1960 to 1998 shows that out of 14 drought incidences, 10 occurred in El Nino years. These extreme events result in extremely high economic losses to the country, for example, drought occurrence in 1982-1983 that was associated with ENSO had caused high losses around 0.4 billion dollars for Indonesia (Boer and Setyadipraktito, 2003). If the extreme events can be predicted earlier, such losses can be reduced. However, results of surveys in several districts in Java indicate that the ability to anticipate extreme climate events is low, as to the ability to accurately forecast weather is not good and the adoption level of climate forecast by the farmers is quite low.

To intensify the effective use of climate forecast information, farmers' knowledge and ability to understand and predict the response of agricultural systems to climate variability should be improved, so that better tailored management decisions in response to favorable or adverse conditions may be implemented and thus crop losses and variability reduced. Information about farmers' perceptions of the use of climate forecast in managing lowland rice-based cropping systems however is limited, especially in this area. This study aimed to specify factors affecting farmers using climate forecast in lowland rice-based cropping system in Jakenan, Central Java; to identify farmers' perceptions of current climate variability and change; and to enhance awareness and adoption of farmers to climate forecast information. Understanding factors related to patterns on a smallholder level and community will provide important information for the policy maker that can be implemented at national scales.

2. Material and methods

2.1 Site description

The survey was conducted in Jakenan sub-district, in Pati District, Central Java, Indonesia. Jakenan is situated 16 km east of Pati. The area covers around 5300 ha and is situated at an altitude of 10-25 m above sea level. The entire area is located in the lowlands with undulating landscapes and the dominant soil type is Tropaqualf. Most people here rely on rice cropping for their livelihoods and hence the study region therefore represents particularly lowland rice-based cropping systems. These systems are mainly characterized as rainfed lowland rice with a dry-seeded crop planted from November to February during the rainy season, followed by transplanted rice from March to June during the dry season (Boling et al., 2004). These predominantly irrigated crops may be followed by an intensified rainfed fallow phase in the form of soybean or mungbean grown from July to October in the dry season. The rainy season in Jakenan generally starts in November and ends in April or May, while the dry season starts in May or June and ends in October. Average annual rainfall is 1596 mm. Average minimum temperature is 23.6 °C and average maximum temperature 31.2 °C. During the last decades, undesirable conditions such as delayed onset, erratic rainfall and flooding have occurred, disturbing crop production.

2.2 Data collection and analysis

The study was based on face to face interviews with smallholder farmers, using a semi-structured questionnaire that consists of open and closed questions. The interview was conducted in four villages in Jakenan sub-district from December 2013 to February 2014. The selection of villages was based on discussion with agriculture and livestock staff of Pati district. The selected villages (Ngastorejo, Tlogorejo, Bungasrejo and Sendangsoko) are considered to be vulnerable to climate risks such as droughts, floods and erratic rainfall, and representative of rice based farming systems in the region. A total of 100 farmers in Jakenan sub-district were selected randomly based on the list of farmers available in each village. Thus each village was represented by 25 respondents.

Respondents were asked about their basic background such as age, education level, family size, and land size; farmers' perceptions related to climate change and impacts; the decision of management commonly practiced in the field; and the ability and habit on climate forecast associated with farming practices. The full questionnaire can be seen in Appendix. The response of respondents was subsequently compiled and analyzed using the SPSS version 22 statistical analysis package.

Farmers' perceptions of current climate variability and change were compared with the climate data recorded by Indonesian Agricultural Environmental Research Institute (IAERI). Daily data of temperature and rainfall was analyzed to specify variability and trends for the period 1983-2013 (30 years) for the selected weather station in the study area (Jakenan sub-district). Jakenan weather station is located at $6^{o}75'$ latitude and $111^{o}17'$ longitude in Pati district. However, since IAERI began to record climate data in 1990, daily data of temperature and rainfall missing prior to that year was downloaded from the National Aeronautics and Space Administration (NASA) prediction of worldwide energy resource for the period 1983-1989 (7 years) for the same study area. The mean and standard deviation of monthly, seasonal and annual rainfall were calculated on t. The box and whisker plot was used to show the distribution of rainfall. The standardized anomalies for rainfall with respect to the long-term average values were used to evaluate inter-annual variability. Linear regression was conducted to determine temperature and rainfall trends.

The availability of climate information is usually disseminated by BMKG. Near term climate information covers monthly forecasts of total rainfall and total rainfall relevant to normal. The monthly forecast is released and updated at the beginning of every month for at least 3 months ahead. Meanwhile, medium term climate information covers the onset of wet or dry seasons and total rainfall and total rainfall relevant to normal during the season. The dry season forecast is released at the beginning of March and that of the rainy season forecast at the beginning of September (Makmur, 2009).

The vulnerability of lowland rice-based cropping systems to climate variability can be identified by using rice production data over time. A line can be fitted to rice production data as the trend line. Thereafter, anomalies from the line fitting data were regarded as responses of the lowland rice-based cropping system to climate variability. Rice production data of the Pati district was downloaded from the Indonesia Ministry of Agriculture (http://www.litbang.pertanian.go.id) and used in this study for the period 1986-2013, as long-term data for the Jakenan sub-district level was not available.

3. Results

3.1 Respondents characteristics

The characteristics of respondents are presented in Table 1. Age of respondents (around 80%) was between 31 and 60 years. Respondents with these ages were in the productive age range and were potentially capable to understand and adopt climate forecast information.

Table 1: Distribution of respondents (n=100) based on age at Jakenan, Central Java, Indonesia.

Age range	Percentage of respondents
20-30 years	6
31-40 years	27
41-50 years	33
51-60 years	24
> 61 years	10

In terms of education level (Table 2), many of the respondents (60%) had attended junior or senior high school and 30% of respondents had elementary school education or none. The level of education is important, as it is said to affect the capability of people to adopt innovation processes (Rogers, 1983). Since the majority of respondents experienced relatively high levels of education, a better adoption of climate forecast information can be expected. In addition, farmers who had highest education level may influence those who had a low education level by introducing and encouraging the role of climate forecast information.

Table 2: Distribution of respondents based on education level at Jakenan, Central Java, Indonesia.

Education level	Percentage of respondents
No education	1
Elementary School	32
Junior High School	22
Senior High School	39
Collage/Academy	6

Family and farm size also corresponded to the characteristics of respondents (Table 3). The size of family generally relates to farmers' income. The higher the number of family members, the more income has to be earned to meet the family needs. Farmer's income particularly derives from their farm productivity. Other family members can contribute to their income by farming or non-farming practices. The size of farm usually determines farmers' income with larger farm sizes resulting in higher income levels.

Around 80% of respondents had two to four children, while others (14%) had one or no children, and 6% had more than four children. For the farm size, 50% of the respondents had one to two ha, around 30% had less than one ha, and 20% had more than two ha. The result of family size is in accordance with the farm size of respondents. A Pearson product-moment correlation coefficient was used to assess the relationship between the household number and farm size. There was a positive correlation between the two variables (p = 0.007), an increase in family size was correlated with an increase in farm size.

Table 3: Distribution of respondents based on family and farm size at Jakenan, Central Java, Indonesia.

Family size	Percentage of respondents
0-3	14
4-6	80
> 6	6
Farm size	**Percentage of respondents**
< 1 ha	29
1-2 ha	49
> 2 ha	22

3.2 Farmers' perceptions on climate variability and change

Based on farmer perceptions, 85% of respondents believed rainfall had decreased whilst 77% considered that temperature had risen and high temperature events have become more common over the last 20 years (Figure 1). Moreover, 80% of interviewed farmers stated that rainfall has become more erratic and all mentioned that the drought and flood events have increased. 20 years ago, the frequency of drought and flood events occurred once in every 8-10 years, but now droughts occur every 2-3 years, while floods occur almost every year. In their opinion, the increase of flood events is due to high intensity of rainfall during the rainy season, the silting of the river of Juwana and deforestation. Dealing with such undesirable conditions, farmers have faced reductions in crop production and crop failure.

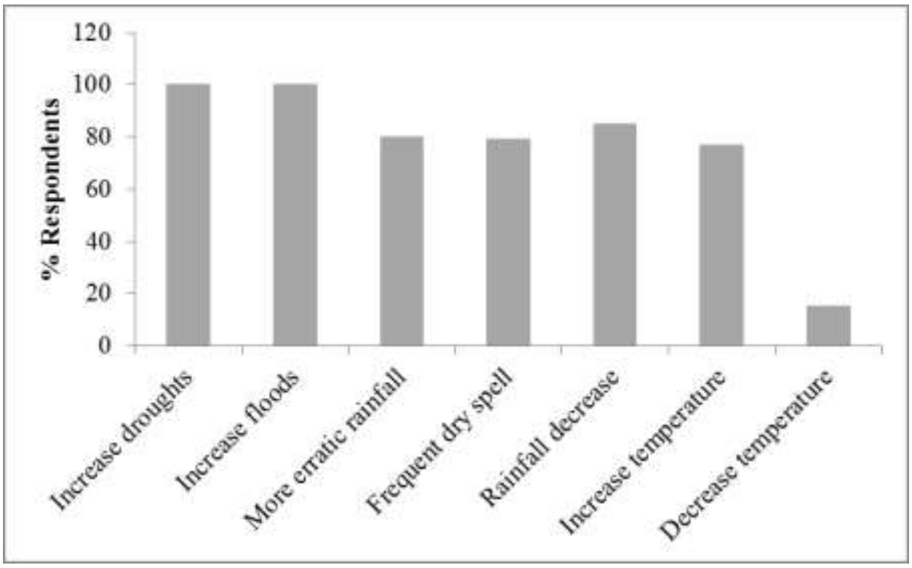

Figure 1: Farmers' perceptions on climate variability and change.
(based on interviews with 100 farmers in Jakenan, Central Java, Indonesia).

3.3 Comparison of climate analysis with farmers' perceptions on climate variability and change

3.3.1 Rainfall pattern and variability

The rainfall pattern over the period 1983-2013 in the Jakenan sub-district was monsoonal, characterized by unimodal rainfall distribution, i.e. simply one peak of the rainy season. The maximum monthly rainfall occurs in December, January and February, while the minimum monthly rainfall occurs during June to September (Figure 2). This circumstance corresponds with the appearance of monsoon in Indonesia. The wet of west monsoon season usually starts from December to February. On the other hand, the dry of east monsoon season starts from June to August. Figure 3 shows a separate box and whisker plot of rainfall over the period 1983-2013. The skew of rainfall distribution of annual and rainy season seems to fall into lower part, meaning that rainfall variability was low, while the skew of rainfall distribution of dry season seems to fall into upper part, indicating that rainfall variability was high.

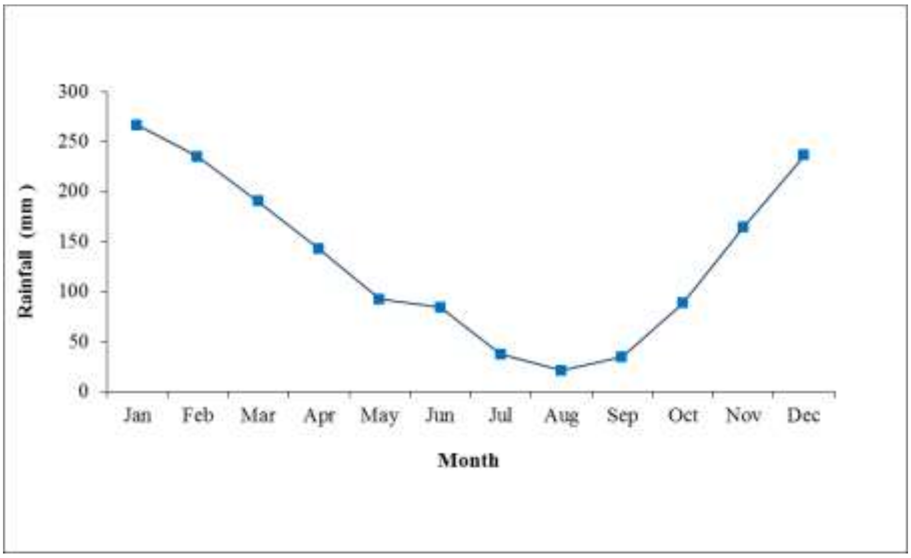

Figure 2: Mean monthly rainfall over the period 1983-2013 at Jakenan weather station, Central Java, Indonesia.

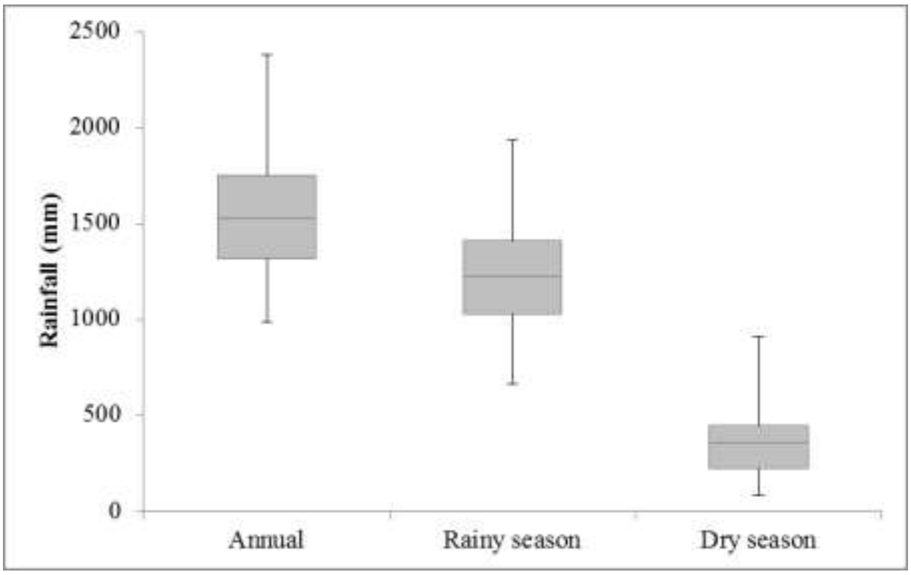

Figure 3: Box and whisker plot of annual and seasonal rainfall (mm) over the period 1983-2013 at the Jakenan weather station, Central Java, Indonesia.

The distribution of seasonal rainfall is an important factor to be considered, as crop production and selection in Jakenan continually takes place in rainy season. During this period, 55% of the years between 1983 and 2013 indicated negative rainfall anomalies relative to the long-term mean. On the other side, the dry season indicated negative rainfall anomalies for 48% of the years (Figure 4a-c). In general, annual and seasonal rainfall in Jakenan showed a slight decrease over the period 1983-2013. The trend was statistically significant ($p < 0.05$) for annual and the rainy season rainfall, but there was no statistically significant trend for the dry season rainfall. Rainfall anomalies in rainy season also corresponded with ENSO events for the year 1987, 1991, 1994, 1997, 2002, 2004 and 2010.

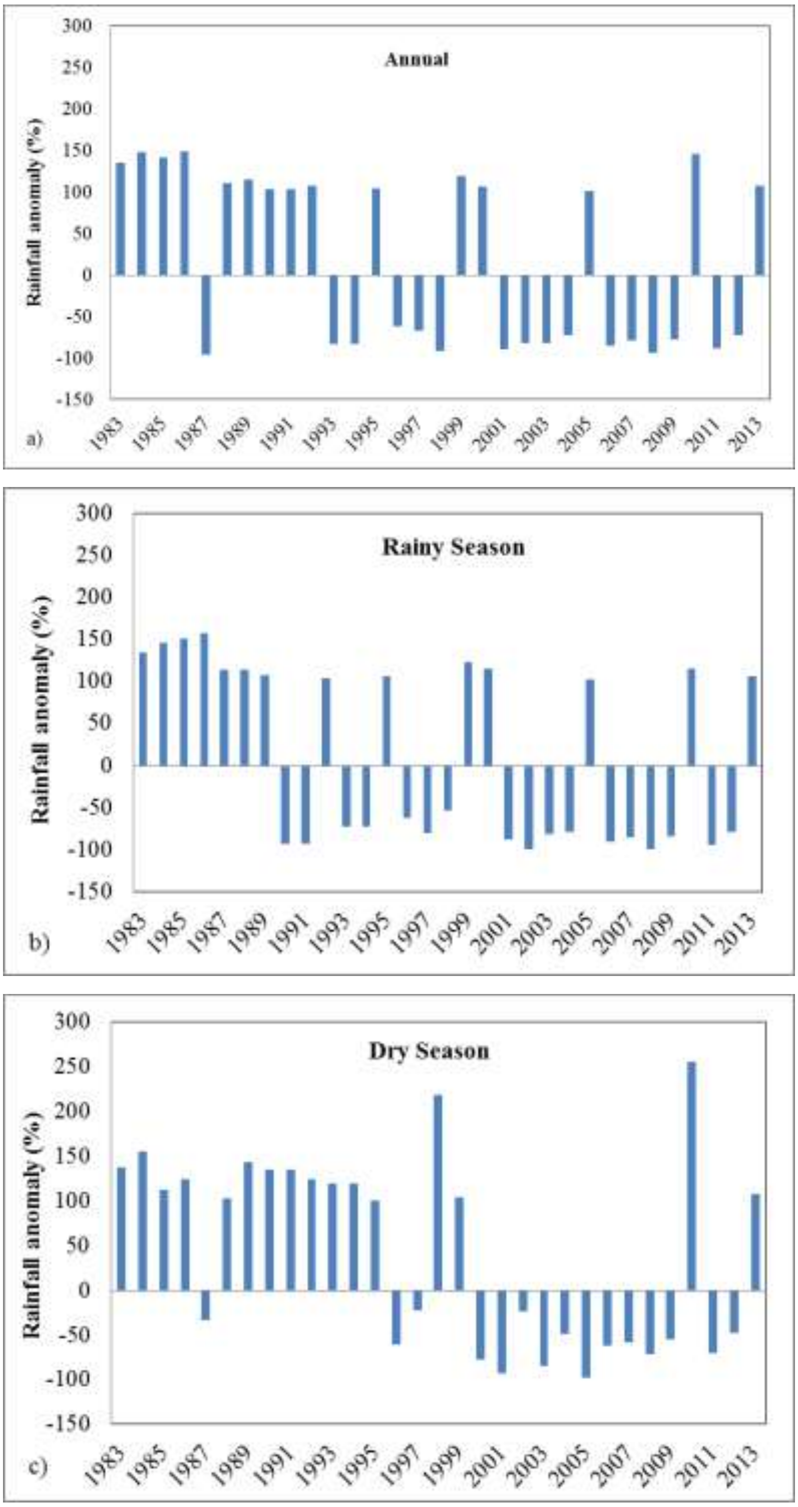

Figure 4a-c: Annual (a), rainy (b) and dry (c) season rainfall deviations from the long-term means over the period 1983-2013 taken from the Jakenan weather station, Central Java, Indonesia.

3.3.2 Temperature changes

Figure 5a-b shows the changes of temperature over the period of 1983-2011 at the Jakenan weather station. The last two years of data, 2012 and 2013 have been removed from the analysis due to extreme temperatures. Temperature trends show that the minimum and maximum temperatures for Jakenan station have not increased for the last 20 years.

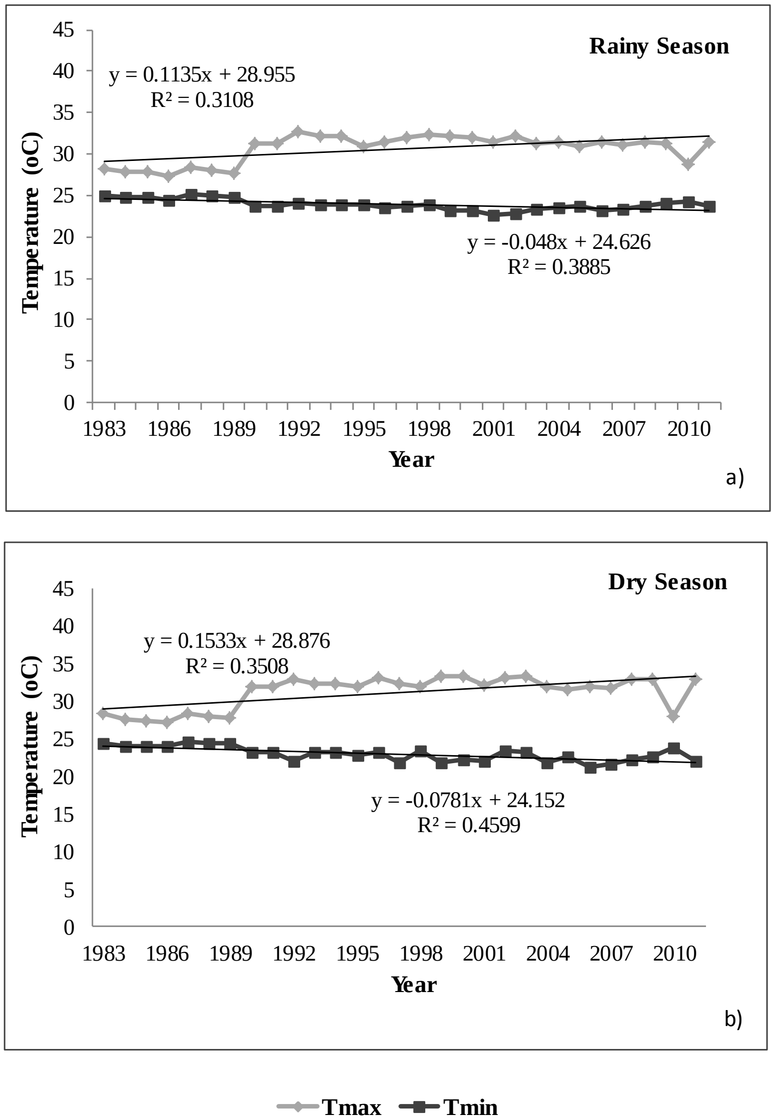

Figure 5a-b: Trend of minimum and maximum temperatures of rainy (a) and dry (b) season over the period 1983-2011 at the Jakenan weather station, Central Java, Indonesia.

3.3.3 Response of lowland rice-based cropping system to climate variability

Rice production trends are generally influenced by factors such as technology interventions, size of planting area and climate variability. To identify responses of lowland rice-based cropping systems to climate variability, factors other than climate variables therefore should be removed by making the line fit to the rice production data. Rice production over the period 1986-2013 in the Pati district was fluctuated and continued to increase after 2007 (Figure 6a). Deviations from the line fitting (anomalies data) then can be regarded as a response of lowland rice-based cropping systems to climate variability (Figure 6b). Figure 6b shows that the negative anomalies of rice production mainly occurred in El Nino years.

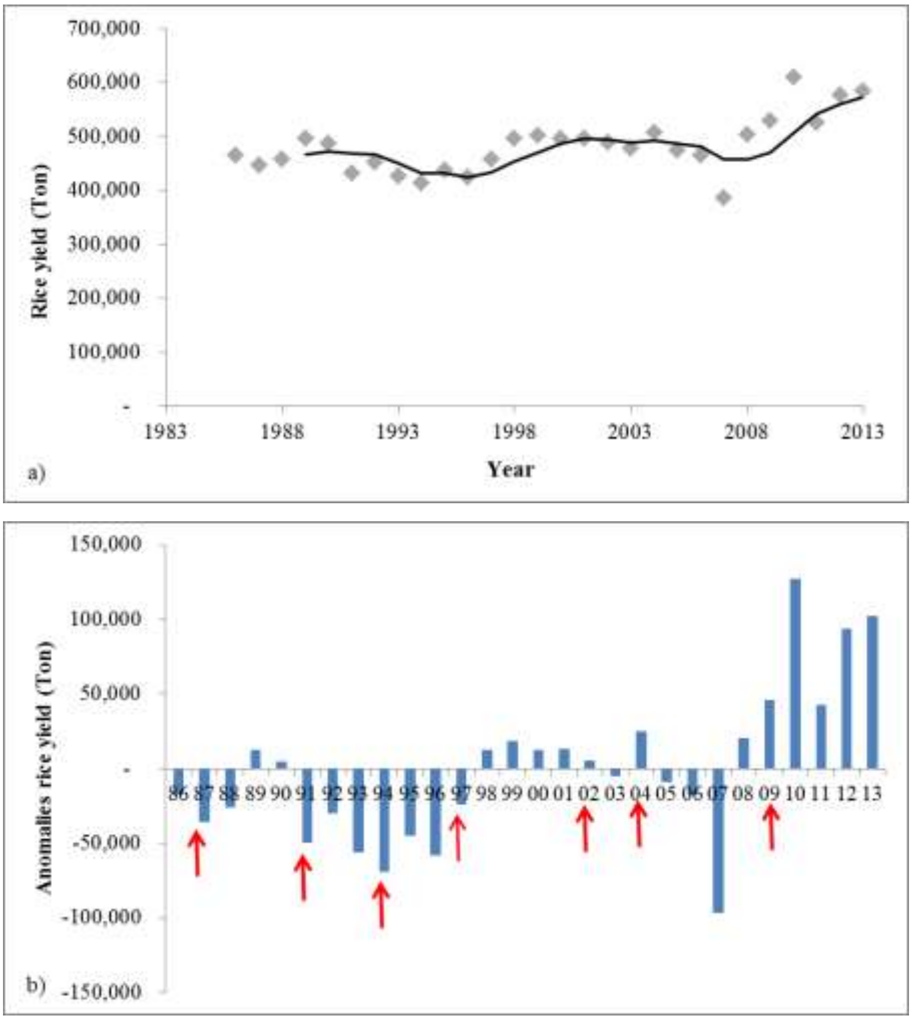

Figure 6a-b: Trend (a) and anomaly (b) of rice production over the period 1986-2013 in the Pati district, Central Java, Indonesia. The arrows indicate El Nino events.

3.4 Crop management practices

In Jakenan, the lowland rice cropping system was commonly characterized by two times of rice planting during the rainy season, followed by legumes during the dry season under rainfed conditions. Almost 80% of the interviewed respondents in Jakenan indicated rice-rice-mungbean as their main cropping pattern (Table 4). As the crop is grown under rainfed conditions, management practices particularly rely on water availability either from irrigation or rainfall. Considering this, we asked farmers about the factors in determining cropping patterns.

Table 4: Selection of cropping pattern based on farm survey in Jakenan, Central Java.

Cropping pattern	Percentage of respondents
Rice-rice-rice	2
Rice-rice-fallow	5
Rice-rice-mungbean	78
Rice-rice-soybean	11
Rice-rice-maize	1
Rice-maize-fallow	3

The numbers of respondents in Jakenan who consider water availability in determining their cropping pattern are 64%, while other respondents consider tradition (28%) and crop maintenance (8%) as the reason for the selection (Figure 7). This number refers that most farmers notice on water irrigation and rainfall, thus in determining their cropping pattern the rainy season is usually taken into account. In addition, many farmers include the yield price in determining cropping pattern, indicating that they are affected by the market.

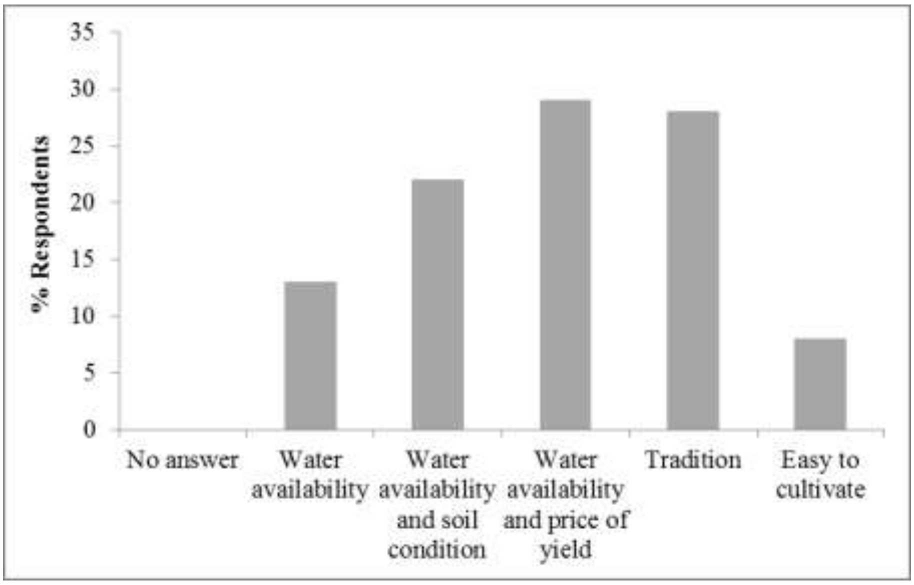

Figure 7: Factors in determining cropping pattern
(based on interviews with 100 farmers in Jakenan, Central Java, Indonesia).

To meet crop water requirements, farmers commonly apply irrigation by pumping water from the river of Juwana, which passes through the Jakenan sub-district. Around 68% of the respondents stated that supplemental irrigation were applied over rice growing season, while other respondents did not apply such management practices (32%). Depending on the size and location of the farm, farmers require high or low cost for pumping water. The bigger the farm size and/or the further the farm is from the river will determine how high such costs will be. Interestingly, farmers do not apply irrigation to legumes over the growing season to save costs. Therefore, they will select a crop that requires less water during the dry season as the water availability relies on the rainfall.

3.5 Effects of climate variability and change

Effects of climate variability and change on crop production and management as perceived by farmers are presented in Table 5. All respondents indicated that climate effects have reduced crop yield and household income. Around 96% of respondents encountered partial or total crop failure and 82% experienced an increase in pest and disease infestation. The increase in pest and disease infestation was felt within respondents as the frequency of drought and floods events increased. For instance, the increase in abundance of brown planthopper and rat typically occurred after floods. In addition, ca. 85% of respondents have changed the cropping pattern and 91% have changed the crop varieties, which was mostly tailored to water availability. Taking everything of the effect of climate variability and changes into account, farmers assured that the food shortage has increased in their region.

Table 5: Effects of climate variability and change on crop production and management as perceived by smallholder farmers in Jakenan, Central Java.

Effects	Percentage of respondents
Major change in cropping pattern	85
Partial or total crop failure	96
Reduced crop yield	100
Change in crop varieties	91
Increase pest and disease infestation	82
Loss income	100
Food shortage	59
Decline consumption	15

3.6 Knowledge on climate forecast

As climate forecast plays a role to improve management practices in farming systems, particularly dealing with climate variability and change as well as climate risk, we therefore asked farmers about their knowledge of climate forecast. According to the survey about 70% of respondents have knowledge of climate forecast, while about 30% of them do not (Table 6). This indicates that farmers, to some extent, have knowledge on climate forecast.

Table 6: Farmers' knowledge of climate forecast based on survey in Jakenan, Central Java.

Description	Percentage of respondents
Do not have knowledge	28
Have knowledge	72

We further asked farmers who have knowledge of climate forecast about how they get the information. Data from the survey showed that farmers get this from several sources (Table 7). 86% of respondents indicated that the information comes from agricultural agencies who regularly visit them, while 32% of respondents mentioned that the forecast information is associated with traditional knowledge and 25% get this from television. Based on farmers' opinion, traditional knowledge is typically related to the condition of fauna or flora, or the position of stars or the moon. However, such knowledge is sometimes not applicable, as the farming systems have changed along with the fauna and flora previously used as indicators.

Table 7: Farmers' sources of climate forecast based on survey in Jakenan, Central Java.

Source of climate forecast	Percentage of respondents
Newspaper	21
Television	25
Traditonal knowledge	32
Agriculture agencies	86
Neighbour	18

3.7 The use of climate forecast in decision making

Most of the respondents do not have the ability to predict the response of lowland rice-based cropping systems to climate variability and to manage the risk that may arise from it. Respondents were then given a follow-up question related to the role of climate forecast information in decision making for farming practices. Around 94% of respondents selected changing the planting time as their main response when using climate forecast information (Table 8). Farmers usually begin planting when the rains start and replaces freshwater in the river (diluting any salt content). Hence, farmers are able to use water to irrigate the crops. Looking at current climatic variability, farmers felt that climate forecast information is not useful for determining planting time. They have to adjust the time of the onset of rain. Planting therefore can be delayed as the onset of rainy season is late. On the other side, planting can begin earlier when the onset of the rainy season is early, but farmers must wait for at least three days in a row of rain to do this. Early planting can also prevent crops from flood risks although farmers may get low yield as the crop is harvested earlier.

Ca. 91% of farmers stated that climate forecast information is used to select crop varieties. The selection of crop varieties is adjusted to match seasonal condition (i.e. drought resistant). Another activity is changing cropping patterns. 73% of farmers interviewed chose changing cropping patterns in the use of climate forecast information. Farmers adjust the cropping pattern from season to season. They can grow rice during the rainy season and when the dry season starts they can select crops that require less water.

Table 8: Role of climate forecast on farming activity based on survey in Jakenan, Central Java.

Farming activity	Percentage of respondents
Crop varieties selection	91
Planting time adjustement	94
Changing cropping pattern	73
Crop risk management	15

4. Discussion

4.1 Farmers' perceptions on climate variability and change

Rainfall variability can influence not only farming systems, but also cropping strategies. As stated by Ravindran (2013), crop management strategies and planning should take the statistical analysis of historical rainfall into account especially if seasonal forecasts are not available. Climate data observed at the Jakenan weather station indicates that there is high annual and seasonal rainfall variability (Figure 4a-c), which is in accordance with the perception of farmers (Figure 1). Rainfall variability shows that the months of July to September experienced lower rainfall, which may lead to dry spells, while the months of December to February had higher rainfall, which often induces flooding (Figure 2). Furthermore, monthly rainfall patterns have been become erratic from year to year (data not shown here). The temperature trend, however, is not in line with farmers' perceptions of increasing temperature over the last 20 years (Figure 1, Figure 5a-b). The distinction of farmers' perceptions for temperature trends and recorded data might be due to an increase in pest and disease prevalence, causing yield reduction. The analysis therefore can provide a basis for farmers to arrange soil preparation and planting time according to the period of reliable and even rainfall distribution. Meanwhile, to deal with dry spell periods during the growing season, farmers are encouraged to adopt water harvesting techniques to irrigate the crops.

Rice production in the Pati district is closely related to El Nino years, as negative anomalies of rice production mainly occur in these years (Figure 6b). El Nino has several impacts on rice production. Firstly, it influences the onset of the rainy season so that the first rice cropping during rainy season is delayed. As a result, the second rice crop is also delayed; hence an increase in drought risk as rainfall at the end of plant growth is reduced. Secondly, El Nino causes dry season rainfall below normal, meaning the water availability is not enough to support plant growth. Thirdly, El Nino leads to the onset of dry season starts earlier than usual, resulting in the second rice crop experiencing drought stress (Boer, 2002). If climate forecast information is known beforehand, measures to avoid such circumstances can be carried out immediately. For instance, when climate forecast shows that the onset of the rainy season is delayed for one to two months, the second rice cropping is not recommended, especially if dry season rainfall is normal or below normal.

Farmers' perceptions on climate variability and change are based on their memories over the last 20 years (Figure 1). This can cause a problem as farmers generally utilize such information in uncertainty environment conditions, dealing with constraints which effects are unclear or unpredictable (Vogel & Brien, 2006). A decline in rainfall perceived by farmers may be related to an increase in temperature. High temperature can influence not only soil moisture, texture and structure but also soil capacity to retain water. When the soil dries without the addition of water either from rainfall or irrigation, crop begin to wilt, causing plant death. The changes in temperature and soil conditions that affect crop water availability, can further affect farmers' perceptions of decreasing rainfall. In addition, frequency of droughts and floods has been increased over the last 10 years. Farmers stated that the increase of drought events were due to dry season rainfall having decreased to the extent that there is not enough water to irrigate crops. As a result, rice production has declined and farmers are occasionally not able to grow crops during the dry season, therefore reducing household income. Comparing farmers' perceptions on rice production with the analysis of trends and anomalies of rice production in the Pati district (Figure 6a-b); a reduction of rice production can be related to the El Nino events as dry season rainfall was below normal.

According to farmer opinion, the main factors that cause the occurrence of floods are a high intensity of rainfall during the rainy season and the silting of the river of Juwana. Deforestation of the Muria forest also contributes flood events in this region. Agriculture agencies mentioned that local government has planned a project to normalize the river, however it has not been approved by central government because it requires substantial funds. If there is no attempt to normalize the river, floods will continue to occur annually. Muria forest areas should be improved by replanting, but it will take 6-10 years for plant roots to absorb the amount of water necessary for them to provide the desired service. Other effects of climate variability and change are yield reduction, crop failure, and pest and disease infestation, which are also observed by farmers. All of these have affected farmers' income and food security, as households have less income and can therefore buy less food. However, this analysis requires a more detailed study that covers cultural conditions, socio-economic and local environmental issues so that comprehensive information can be gathered. Unfortunately, this scope is beyond our study.

4.2 Factors affecting farmers in using climate forecast in lowland rice-based cropping system

Crop management practices such as cultivation and irrigation management are the first factor that affects farmers in using climate forecast in lowland rice-based cropping system. These management practices usually will consider cropping patterns that are selected by farmers in order to improve crop production. Most of the respondents (80%) select rice-rice-mungbean as their main cropping pattern since they have to adjust to water availability (Table 4, Figure 7). To reach optimum growth, crops require large quantities of water. Crop growth is therefore influenced by the amount and timing of water applied over the production period. Particular stages of crop growth are more sensitive to water stress compare to others (Kramer, 1969). Water status also affects crop vigor and its resistance to insects and diseases infestation. Water should be managed properly so that optimum growth can be achieved and crop production improved. This finding is in line with the study conducted in Lombok Island, Indonesia, which showed that farmers in dry land areas considered water availability as the main factors in deciding cropping patterns (Sayuti et al., 2004).

Since water management is important for the success of crop growth, farmers rely on irrigation availability and rainfall to irrigate crops. 68% of interviewed farmers applied supplemental irrigation to meet crop water requirements. Irrigation is particularly applied to water-based rice crop, while dry season crops (i.e. mungbean, soybean) depend on rainfall or residual soil water. A number of farmers (32%) did not apply supplemental irrigation and simply relied on rainfall to irrigate their crops. Water management is then based on cost of supplemental irrigation, where farmers must consider whether the costs of such inputs are comparable to the yield obtained. Pumping water from the river to the field is costly, farmers have to set the installation up and buy fuel to operate the pump. To minimize the costs, farmers will select crops that require less water during the dry season so they do not have to apply irrigation. As a consequence, farmers may get low yield, but they are still able to sell to the market, although income will be low. A solution has been implemented among farmers through the installation of supplemental irrigation conducted by farmers within groups. This way costs can be shared or spread out, while the operation of such systems is carried out alternately. This issue needs serious attention from farmer communities and government to help deal with water availability.

Knowledge on climate forecast is another aspect that affects the use of climate forecast (Table 6). Based on the farm survey, farmers of a productive age and a better education level were able to receive and adopt climate forecast information (Table 1, Table 2). The productive age of a farmer coupled with a comparatively better education leads to a better interpretation of complex situations and adoption of innovation processes (Rogers, 1983; World Bank, 2002). Knowledge on climate forecast allows farmers to transfer technology related to climate forecast information. Agricultural agencies, therefore, play an important role in delivering climate forecast information to the farmers. Group discussions are held regularly in order to improve their knowledge and skill related to climate forecast information. Also, being a part of group enable farmer to easily access climate forecast information, helping in decision making for farming practices.

The last aspect that influences farmers in using climate forecast is the process of decision making for farming practices. To this day, farmers use the information to adjust planting time and to select appropriate crop varieties in order to cope with climate variability (Table 8). Survey studies have shown that adjusting planting time is an effective strategy to cope with climate variability (Traerup and Mertz, 2011; Kasie et al, 2013). Farmers have to adjust planting time to the onset of rainy season. Planting can therefore either be delayed if rainy season starts late, or earlier it starts early. However, the ability to use climate forecast information to manage climate risk was limited (i.e. coping with El Nino years). In other words, climate forecast information has not been used effectively by farmers, as their adoption level of it was low. Governments should therefore give more attention to this, so that farmer knowledge and skill in relation to climate forecasts can be improved and crop yield losses minimized.

5. Conclusions

This study compared farmers' perceptions on climate variability and change with historical data. It is also explained several crop management practices that are commonly practiced in the field along with the use of climate forecast information in farming practices as responses to the perceived climate variability. Most of the farmers observed a declining trend of rainfall and an increase of drought and flood events over years that caused a reduction of crop production. These perceptions fit with historical data on rainfall and crop production, which show a declining trend. However, observations concerning an increase of floods do not fit with historical data. Farmers believe an increase in floods is related to the high intensity of rainy season rainfall, the silting of the river of Juwana, and deforestation.

Several factors that affect farmers in using climate forecast information are management practices, knowledge on climate forecast and the process of decision making for farming practices. Regarding crop management, the majority of farmers selected rice-rice-mungbean as their main cropping pattern – this choice is mostly based on water availability. Better knowledge on climate forecast enable farmers to interpret complex situation and adopt innovation.

The use of climate forecast information in coping with climate variability was mainly related to planting time adjustment and the selection of appropriate crop varieties. The onset of the rainy season is crucial, since the first rice cropping takes place in the rainy season. The delay of the first rice cropping will affect the second rice cropping and will therefore impact crop growth and production. Farmer adoption levels were low considering climate risk management, especially in coping with El Nino events. Farmers did not know how to deal with some crop management strategies during El Nino years. In addition, information on how the climate forecast could be useful to dry season crops and the level of skill at that time of the year is limited. Future research is needed to fill such information gaps.

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Appendix: Questionnaire for respondents

1. General information

a) Enumerator's name	
b) Date of interview (dd/mm/yyyy)	
c) District	
d) Sub-district	
e) Village	
f) Main cropping system	

2. Respondents' information

a) Name of the respondent		
b) Gender	M	F
c) Education *		
d) Name of the respondent		
e) Age of the respondent		
f) Numbers of years in farming experiences		
g) Number of household member		

***No formal schooling (1), elementary school (2), junior high school (3), senior high school (4), collage/academy (5)

3. Land size and status

Land size	a) owned	b) shared	c) rented
a) <1 Ha			
b) 1-2 Ha			
c) >2 Ha			

4. Access and management of water resources (put "X" if not relevant)

Descriptions	Sources of water			
	River	Reservoir	Well	Other
a) Privately owned				
b) Communally owned				
c) Duration of irrigation (hours per one set of irrigation)				
d) Cost to develop (IDR/structure)				
e) Cost of irrigation with oil (IDR/ha)				
f) Cost of irrigation with electric (IDR/ha)				
g) Other costs of investments in irrigation (IDR/ha)				
h) Areas that the structure can irrigate (ha)				

5. Major limitation: most restricting resources for crop production

Resources	Rank	Resources	Rank
a) Drought and flood		e) Options to sell crop	
b) Land access (area and ownership)		f) Information on how to improve crop	
c) Soil quality (related to fertility)		g) Labor availability (family/hired)	
d) Access to fertilizer/new seed/techno		h) Investment capital	

Rank descending: most limiting resources rank=1

6. Crop inputs, production and productivities by seasons

Items	Seasons					
	Rainy		Dry I		Dry II	
a) Crop name (cropping pattern)*						
b) Variety						
c) Water sources**						
d) Type of irrigation (furrow, flood)						
e) Tillage (1=tractor, 2=traditional)						
f) Seed rate (kg/ha)						
g) Sowing date (dd/mm)						
h) Seed sources***						
i) FYM use (kg/ha)						
j) Green manure (kg/ha)						
k) Fertilizer: 1. Urea (kg/ha)						
l) Fertilizer: 2. SP36/TSP (kg/ha)						
m) Fertilizer: 3. (kg/ha)						
n) Herbicides (expense IDR/local units)						
o) Fungicides (expense IDR/local units)						
p) Harvesting date (dd/mm)						
q) Human labor (days/local units for all activities)						
r) Bullock power (days/local units)						
s) Machine power (hrs/local units)						
t) Any other cost (IDR /local units)						
u) Costs of irrigation facilities (IDR/local units)						
v) Harvesting (machine (1), manual (2))						
w) Threshing (machine (1), manual (2))						
x) Main products (kg/ha)						
y) Secondary products (kg/ha)						
z) Price of main product(IDR/kg)						
aa) Price of secondary product(IDR/kg)						

*Crop code: 1=Rice, 2= Mungbean,3= Soybean, 4=Maize, 5=Others specify , 6=Fallow

** Water sources code: 1=River, 2=Reservoir, 3 = Well, 4= Rainfed, 5=. Others specify

***traditional=1, private=2, government =3, others=4

6.1 Unit costs of major inputs

Details	Unit	Currency (IDR)
a) Bullock power	Days	
b) Fertilizer: 1. UREA	100 kg	
c) Fertilizer: 2. SP36/TSP	100 kg	
d) Fertilizer: 3.	100 kg	
e) FYM	100 kg	
f) Human labor	Days	Male----- Female
g) Machine power	hrs	
h) Seed	kg	

7. Crop pattern decision

Reason for crop pattern decision:	
a) Water availability	yes/no
b) Water availability and soil conditions	yes/no
c) Water availability and price of yield	yes/no
d) Tradition	yes/no
e) Easy to cultivate	yes/no
f) Do not know	yes/no

8. Knowledge of climate forecast

Do you have knowledge of climate forecast?	
a) Yes	
b) No	
c) No response	

9. What are your sources of climate forecast information?

a) Newspaper	(yes/no)
b) TV	(yes/no)
c) Radio	(yes/no)
d) Traditional knowledge	(yes/no)
e) Agriculture agencies	(yes/no)
f) Neighbor	(yes/no)
g) Other (specify)	(yes/no)
i) Do not know	(yes/no)

10. Major shocks encountered

Over the last twenty years have you observed	
a) Increase droughts	yes/no
b) Increase floods	yes/no
c) More erratic rainfall	yes/no
d) Frequent dry spell	yes/no
e) Rainfall decrease	yes/no
f) Increase temperature	yes/no
g) Decrease temperature	yes/no

11. Effects of shocks

Over the last twenty years have you observed	
a) Major change in cropping pattern	yes/no
b) Partial or total crop failure	yes/no
c) Reduced crop yield	yes/no
d) Change in crop varieties	yes/no
e) Increase pest and disease prevelance	yes/no
f) Less income	yes/no
g) Food shortage	yes/no
h) Decline consumption	yes/no

12. Role climate forecast on farming practices

a) Crop varieties selection	yes/no
b) Sowing time adjustment	yes/no
c) Changing cropping pattern	yes/no
d) Crop risk management	yes/no
e) Other (specify)	yes/no

III. Intensification of the fallow phase on rainfed lowland rice and the opportunity to grow legume crops at a range of management practices and agro-climatic conditions in Central Java, Indonesia: A simulation study.

1. Introduction

The potential of rainfed lowland rice is widely spread in Indonesia. Three big provinces of Java have the largest rainfed lowland area with a total of 1 M ha. Central Java has the largest area, with 293.600 ha, or 30% of the total area (Amien and Las, 2000). In Central Java, the cropping pattern mainly consists of a dry-seeded rice crop, called *gogorancah*, followed by transplanted rice (*jerami walik*) cultivated with minimum tillage. *Gogorancah* is grown during the wet season from November to February, while *walik jerami* is grown immediately after the harvest of *gogorancah* from March to June (Boling et al., 2004). Rice, however, has limited success if grown after the rainy season without irrigation. If there is sufficient residual soil moisture, farmers may grow legumes such as mungbean, soybean and peanut in lowland areas after rice (Boling et al., 2000). Legumes can be grown either preceding or following rice and are usually used as a source of food, animal feed, fodder or green manure and may improve the income of farmers (Buresh and De Datta 1991; Chandrasekaran et al. 1996).

The inclusion of legumes into a rice based cropping system has been shown to improve soil structure and fertility, providing the basis for rice yield enhancement and the opportunity to exploit the water stored in the soil profile (Buresh and De Datta, 1991; Cook et al., 1995). Legumes are not only able to fix atmospheric N, thereby enhancing soil N fertility, but they also play a role in diversifying the agricultural system, which works towards a systems of sustainable rice production (Schulz et al., 1999). Rice-legume systems, however, encounter constraints related to soil and climate conditions. Plant growth following rice is often poor as soils are typically plowed, puddled and kept flooded during land preparation and at least part of rice growing season. Such practices destroy soil structure, decrease organic matter content and provide a poor growing environment for following crops (De Datta and Hundal, 1983; Singh et al., 2005). In addition, puddled soils can restrict legume root growth (Chandrasekaran et al. 1996). In rainfed lowland rice areas, as the climate is warm throughout the year, temperature differences tend to be higher between night and day than between seasons. With adequate solar radiation, water availability is largely dependent on rainfall (Amien and Las, 2000). In Central Java, rainfall largely comes in the form of a monsoon, with distinct wet and dry seasons. The rainy season will start in October and the water supply can be sufficient for two rice crops in one year. However, in other areas the duration of the wet season is only sufficient for one rice crop due to erratic rainfall, leading to increased drought in some areas and less available water for the next crop. Studies have shown that drought is an important factor in the reduction of rainfed rice yield in Jakenan, Central Java (Setyanto et al., 2000; Boling et al., 2004; Boling et al., 2007).

To maximize the opportunity for growing legumes in rainfed lowland rice areas, appropriate management practices are required to enable the crops to grow properly after the rice crop. Research has demonstrated the importance of appropriate management practices, such as soil and crop management, fertilizer application, selection of variety and pest management to stabilize legume yields and maintain long-term soil fertility (Schulz et al., 1999; So and Ringrose-Voase, 2000). However, information on how to manage the crops related to climate variation are limited, especially concerning sequences of rice and legumes as stable and sustainable rainfed lowland rice based cropping systems. Therefore, a systems assessment is required to improve the understanding of the correlation among the components of complex systems, to give more insight into processes and verify the consequences of management as well as explore the potential for modification.

Crop simulation models can be used to quantify crop performance and understand the interaction between crops, soil, weather and management (Hoogenboom, 2000; Amien, 2004). Simulation models also have the ability to evaluate alternative strategies and to allow information required to assess risk as well as to explore other scenarios and long-term issues beyond the experimental data base to other sites and seasons (Keating et al., 1991; Probert et al., 1998b). Soltani and Sinclair (2012) highlighted that crop models are used to study the response of crop yield and other crop variables to management options.

The Agricultural Production System Simulator (APSIM) model is a versatile software system that can simulate production and environment consequences of agricultural production systems (Carberry et al., 1996; Holzworth et al 2014). APSIM has the ability to simulate a range of crop and soil processes in response to management options that include crop sequences and species mixtures. Furthermore, APSIM was developed primarily as a research tool to investigate on-farm management practices, especially where outcomes are affected by variable climatic conditions (Holzworth et al., 2006). Numerous simulation modeling studies have been carried out using APSIM in modeling the performance of legumes in cereal based cropping systems (Probert et al., 1998a; Mohanty et al., 2012). However, the ability of crop simulation models to predict the performance of legumes in rice based cropping systems, particularly concerning various management practices and agro-climatic conditions is limited. This study therefore aimed to identify legumes performance potential at various sowing times, residue treatments, soil types and initial water levels. It also set out to evaluate the performance of the model for growing legumes under different agro-climatic conditions in rainfed lowland rice systems.

2. Material and methods

2.1 Site description

Four sites where legumes and rice systems are often used in Central Java, Indonesia were selected for simulation analysis. Selected sites: Jakenan (6°45’ S, 111°10’ E), Brebes (6°84’ S, 109°06’ E), Kebumen (7°67’ S, 109°65’ E), and Sukoharjo (7°97’ S, 111°10’ E). Based on daily weather records from 1983 to 2013, annual average rainfall of Jakenan, Brebes, Kebumen and Sukoharjo sites were 1594, 1936, 2529 and 1680 mm, respectively. Rainfall occurs more frequently between October and May, which comprises the rice growing season (Jakenan 1416; Brebes 1689; Kebumen 2287; Sukoharjo 1532 mm). For all sites, an average daily temperature is similar and highest from September to October (28.2-32.4^{o}C) and lowest from July to August (21.4 to 24^{o}C) (Figure 1).

2.2 APSIM and component modules

The APSIM version 7.5 modules used in this study were Mungbean, SoilN (soil nitrogen), SoilWat (soil water balance), and Residue (surface residue). These modules were connected via a central APSIM engine to simulate mungbean cropping systems. Details of mungbean growth development parameters and modules are described by

Robertson et al. (2002) and Keating et al. (2003). The details of SoilN, SoilWat and Residue modules are reported by Probert et al. (1998b) and Keating et al. (2003).

2.3 Climate data

To simulate all the modules, APSIM requires daily climate data (maximum and minimum temperatures, rainfall and solar radiation). For the Jakenan site, daily temperature, rainfall and solar radiation data for the period 1990-2013 were obtained from Indonesian Agricultural Environmental Research Institute (IAERI). However, since IAERI only began to record climate data in 1990, daily data for temperature, rainfall and solar radiation missing prior to that year was downloaded from the National Aeronautics and Space Administration (NASA) prediction of worldwide energy resources for the period 1983-1989 (7 years). For the Brebes, Kebumen and Sukoharjo sites, daily temperature and solar radiation data for the period 1983-2013 was downloaded from the National Aeronautics and Space Administration (NASA) and daily rainfall data for the same period from the Asian Precipitation Highly Resolved Observational Data Integration towards the Evaluation of Water Resources (APHRODITE) (www.chikyu.ac.jp/precip/index.html).

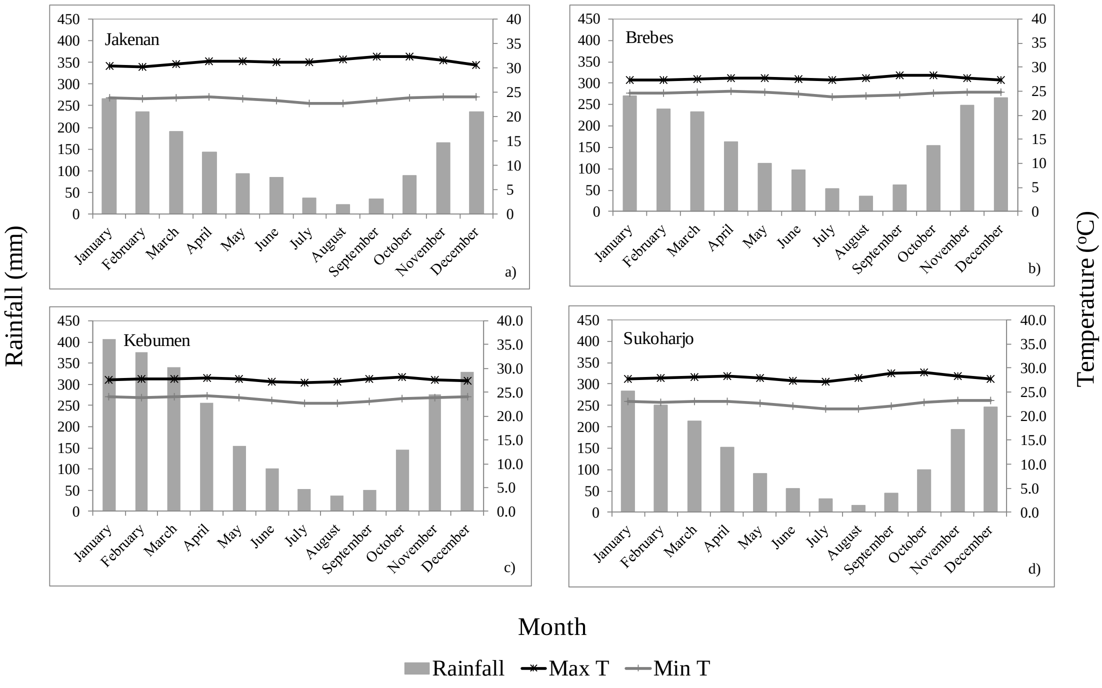

Figure 1: Long-term (1983-2013) monthly average rainfall and minimum (min T) and maximum (max T) temperatures for a) Jakenan, b) Brebes, c) Kebumen and d) Sukoharjo in Central Java, Indonesia.

2.4 Crop system and management

The selection of mungbean in this study follows the most common farmer practice as identified via the survey presented in Chapter II. Simulated in APSIM, mungbean was grown at a density of 20 plants m^{-2} using the Berken cultivar. Soil mineral N was reset to an initial condition of 20 kg N ha^{-1} and surface organic matter was reset to an initial condition of 2000 kg rice stubble ha^{-1} at the start of each crop - initial soil water depended on the treatment, described in the next section. Irrigation (50 mm) was applied once at sowing. Mungbean was grown during the dry season between June and September following the common practices employed by the farmers. These crops did not receive fertilizer and irrigation over the growing season. Soil was not tilled, as mungbean was sown directly after harvesting rice.

2.5 Scenario analysis

Crop model simulations were developed to identify mungbean performance at various management practices and agro-climatic conditions, particularly when it was grown after rice during the dry season. These practices were examined for four sites in Central Java (Jakenan, Brebes, Kebumen and Sukoharjo) using climate data from 1983 to 2013. Details of practices are described as follows:

(i) Sowing time: sowing windows were set from 1st June to 30th June for early, 1st July to 30th July for mid, and 1st August to 30th August for late sowing for each crop. The crop was sown at the first day of each sowing window.

(ii) Residue treatment: crop residues were set retained and removed for each sowing time.

(iii) Soil type: three soil types (clay, loam and sandy) were set following standard values in the SoilWat module for each residue treatment (Table 1).

(iv) Plant available water (PAW): seven values for PAW were set from 10 to 70 mm at an interval of 10 mm of water for each soil type. These values are considered representative of low, medium and high PAW.

All of the above practices were arranged using the user interface of APSIM's Manager and SoilWat module. Simulations were initiated on the 1st July 1983 until the 31st December 2013.

Table 1: Description of water and soil water of soil types in this study.

Descriptions	Clay	Loam	Sand
Organic carbon in the top soil (%)	1.2	1.3	0.5
Plant available water capacity (mm)	111	90	66
Bare soil runoff curve number	73	73	73
Summer and winter U	6	4	3
Diffusivity constant	40	88	250
Diffusivity slope	16	35	22
SWCON	0.3	0.5	0.7

2.6 Data analysis

She simulated mungbean growth data was processed to understand how productivity varied over seasons and treatments. Cumulative distribution functions were used to calculate the probability of each outcome for the various management practices and agro-climatic conditions for each study site. To understand performance, simulated mungbean yields were compared at different levels of rainfall accumulation over their growing season for each site. Rainfall accumulation data was sorted and grouped into 4 to 6 levels from 0 to 900 mm at an interval of 150 mm. The frequency of occurrence was calculated for each level.

3. Results

3.1 Probability of mungbean performance at various sowing times, soil types and levels of PAW

As field validation was not possible in this study, simulated yields were compared to actual farmer yields. Farmers generally achieve yields about 1.2 ton ha^{-1}, whereas the potential yield in this region is 1.5 to 2 ton ha^{-1} (Radjit et al., 2014). The range of simulated yields falls into the range of actual yields.

To identify the performance of mungbean at a range of agro-climatic conditions, the APSIM model was used to simulate grain yields of mungbean at various sowing times and soil types with different levels of PAW (specifying plant available water relative to crop lower limit 15) for four sites. Three out of seven levels of PAW (10, 40 and 70 mm) are considered to represent the low, medium and high PAW. As simulated yields of mungbean do not show differences in removed and retained residue treatments, the average of both treatments is given.

A comparison of mungbean yield variability across all sites can be determined through cumulative distribution functions. Figure 2a-d presents the variability of mungbean at various sowing times and soil types, and at 10 mm of PAW. At Jakenan, 40% of seasons for all soils and sowing times resulted in yields <750 kg ha^{-1} and 80% <400 kg ha^{-1}. At all other sites, the spread of yields is generally >700 kg ha^{-1}. For Kebumen, the yield range showed a narrower spread between 500 and 1250 kg ha^{-1} indicating fewer years of rainfall that may support yields above 1250 kg ha^{-1}. Sukoharjo had the widest distribution of yields between 340 and 1370 kg ha^{-1} showing more years with rainfall that may support yields up to 1370 kg ha^{-1}.

At medium PAW (40 mm), the variability of mungbean yield indicated that the spread of yields is mainly >900 kg ha^{-1} at Brebes, Kebumen and Sukoharjo, whereas at Jakenan, 40% of seasons for all soils and sowing times resulted in yields <950 kg ha^{-1} and 80% <500 kg ha^{-1} (Figure 3a-d). Similar to the yield range at 10 mm of PAW, Kebumen showed the narrowest distribution of yields between 670 and 1270 kg ha^{-1} indicating that there are fewer years with rainfall that can support yields above 1270 kg ha^{-1}. For Jakenan, the yield range showed a wider spread between 340 and 1300 kg ha^{-1}, indicating more years with rainfall that can support yields up to 1300 kg ha^{-1}.

At the highest PAW (70 mm), the variability of mungbean yield at Jakenan showed that 40% of seasons for all soils and sowing times resulted in yields <1000 kg ha^{-1} and 80% <600 kg ha^{-1}. At all other sites, the spread of yields is generally >1000 kg ha^{-1}. Similar to the yield range at 10 and 40 mm of PAW, Kebumen showed the narrowest distribution of yields to be between 710 and 1290 kg ha^{-1}, showing fewer years with rainfall that can support yields above 1290 kg ha^{-1}. For Jakenan, the yield range showed a wider spread of between 430 and 1340 kg ha^{-1}, indicating more years with rainfall that can support yields up to 1340 kg ha^{-1}.

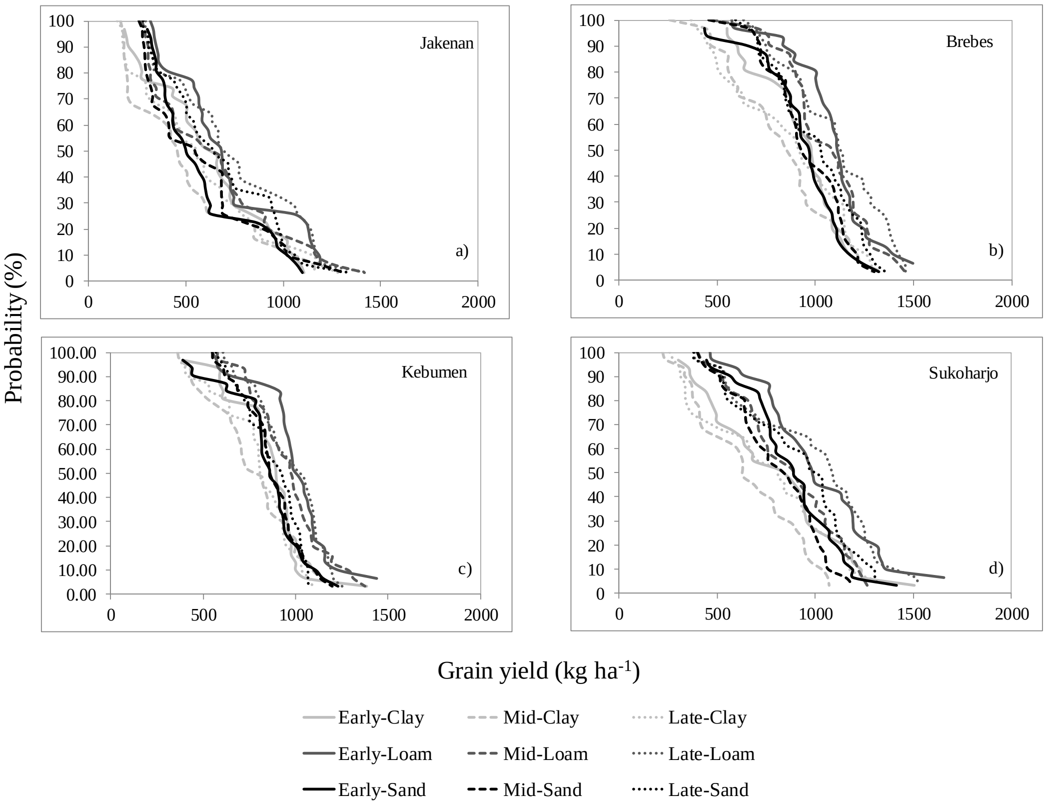

Figure 2a-d: Exceedance probability for APSIM simulations of mungbean grain yield (kg ha^{-1}) for a) Jakenan, b) Brebes, c) Kebumen and d) Sukoharjo at different sowing times (early, mid and late sowing) and soil types (clay, loam and sandy soil) with 10 mm of PAW across the 1983-2013 climate records for each site.

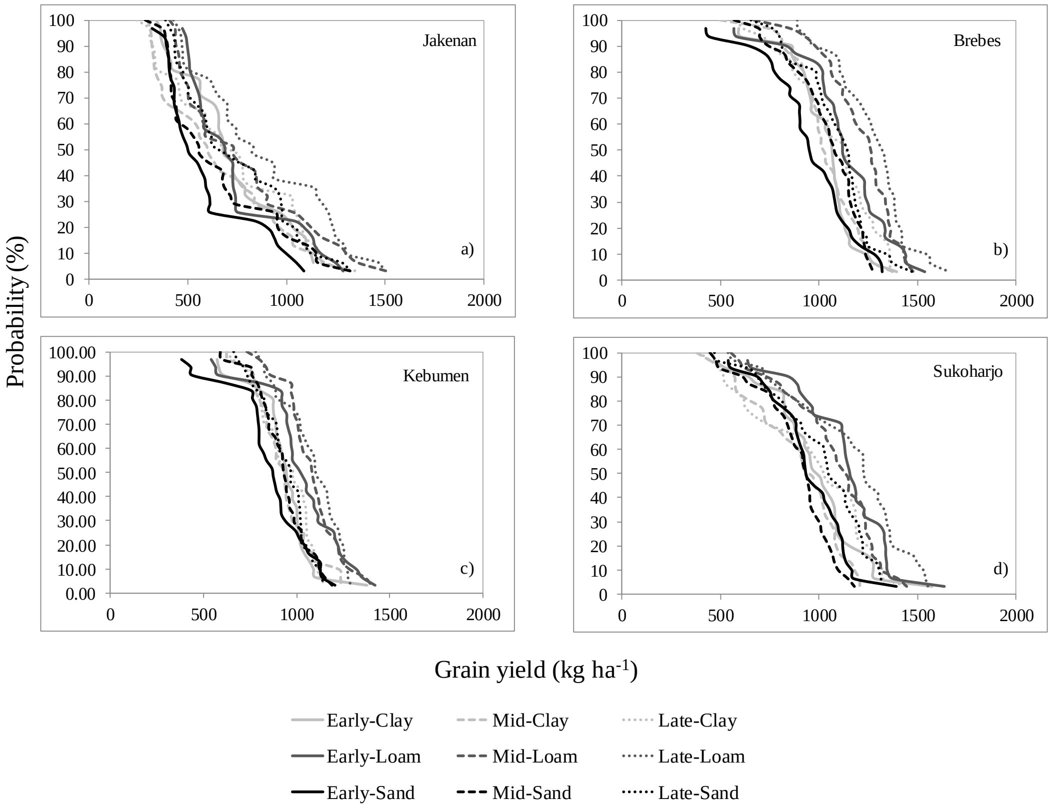

Figure 3a-d: Exceedance probability for APSIM simulations of mungbean grain yield mungbean (kg ha^{-1}) for a) Jakenan, b) Brebes, c) Kebumen and d) Sukoharjo at different sowing times (early, mid and late sowing) and soil types (clay, loam and sandy soil) with 40 mm of PAW across the 1983-2013 climate records for each site.

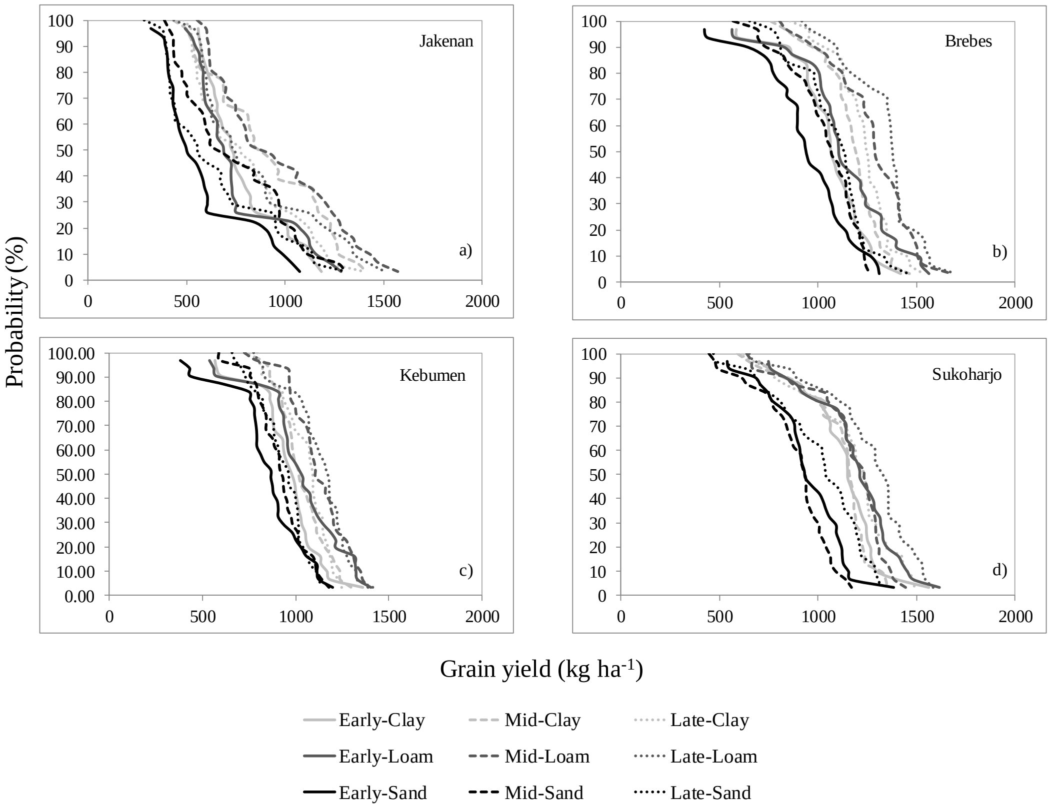

Figure 4a-d: Exceedance probability for APSIM simulations of mungbean grain yield mungbean (kg ha^{-1}) for a) Jakenan, b) Brebes, c) Kebumen and d) Sukoharjo at different sowing times (early, mid and late sowing) and soil types (clay, loam and sandy soil) with 70 mm of PAW across the 1983-2013 climate records for each site.

3.2 The performance of mungbean yields at three soil types and levels of PAW

At all sites but Jakenan, the average grain yields when 10 mm of PAW is applied are lowest in the clay soils, followed by the sandy, and loam soils (Table 2). Clay soils proved to have a wider range of grain yields indicating higher risk of a poor harvest, followed by the loam soils. In the sandy soils, grain yields are comparatively reliable across seasons at low levels of PAW. The response to PAW is increasingly high at higher levels of PAW with relatively smaller coefficient variance, indicating that there is less variability in grain yield from season to season. The grain yields at 70 mm of PAW are the highest in the loamy soils followed by clay soils, and sandy soils for all sites. In terms of values, grain yield is around 940 kg ha^{-1} at Jakenan, whereas at the three other sites grain yield is >1000 kg ha^{-1}.

Table 2: Simulated average yield and coefficient of variance (standard deviation/average) for different soil types (clay, loam and sand) at 4 sites in Central Java in response to different levels of PAW (10, 40 and 70 mm) based on APSIM runs from 1983-2013.

Sites	Soil types	Grain yield at (kg ha^{-1})					
		10 mm of PAW		40 mm of PAW		70 mm of PAW	
Jakenan	Clay	493	(0.59)	642	(0.45)	792	(0.31)
	Loam	737	(0.43)	869	(0.37)	941	(0.32)
	Sand	797	(0.24)	724	(0.36)	720	(0.36)
Brebes	Clay	828	(0.32)	1033	(0.19)	1189	(0.12)
	Loam	1072	(0.22)	1236	(0.15)	1300	(0.15)
	Sand	1037	(0.16)	1043	(0.18)	1033	(0.18)
Kebumen	Clay	750	(0.25)	900	(0.15)	1006	(0.13)
	Loam	938	(0.18)	1050	(0.15)	1088	(0.16)
	Sand	894	(0.15)	895	(0.15)	886	(0.15)
Sukoharjo	Clay	733	(0.44)	934	(0.31)	1126	(0.19)
	Loam	970	(0.33)	1135	(0.24)	1228	(0.18)
	Sand	1002	(0.17)	974	(0.23)	967	(0.22)

3.3 The performance of mungbean yields at three sowing times and levels of PAW

In simulations across all sites, when 10 mm of PAW is applied the average grain yields are lowest for mid-sowing, followed by early and late sowing (Table 3). The mid-sowing scenarios have a greater magnitude of grain yields showing a higher risk, followed by early sowing. In the case of late sowing, grain yields are relatively stable across seasons at low levels of PAW. The response to PAW is increasingly high at higher levels of PAW. The coefficient of variance decreases here, indicating that there is less variability in grain yield from season to season. The grain yields at 70 mm of PAW are higher at mid and late sowing compared to early sowing for all sites. At Jakenan, grain yield is around 950 kg ha^{-1}, whereas at Kebumen, Sukoharjo and Brebes, grain yield is around 1000, 1200 and 1300 kg ha^{-1}, respectively.

A relationship between water supply from sowing to maturity (extractible soil water at sowing plus rainfall until maturity) and yield on loam soil and at late sowing for four sites is presented in Figure 5. A non-linear relationship with a linear part of the curve reaching a plateau was suggested by the model, indicating that additional water does not increase yield. Additionally, for a site like Jakenan, perhaps a short season variety would do better if rainfall runs out later or is well distributed. In addition, the cultivar may not be available throughout the entire period, thus limiting yield.

Table 3: Simulated average yield and coefficient of variance (standard deviation/average) for different sowing time (early, mid and late sowing) in loamy soils at 4 sites in Central Java in response to different levels of PAW (10, 40 and 70 mm) based on APSIM runs from 1983-2013.

Sites	Sowing time	Grain yield (kg ha^{-1}) at		
		10 mm of PAW	40 mm of PAW	70 mm of PAW
Jakenan	Early	678 (0.39)	724 (0.32)	741 (0.28)
	Mid	635 (0.50)	761 (0.41)	966 (0.22)
	Late	737 (0.43)	869 (0.37)	941 (0.32)
Brebes	Early	1031 (0.20)	1082 (0.22)	1080 (0.23)
	Mid	1028 (0.20)	1183 (0.15)	1268 (0.16)
	Late	1072 (0.22)	1236 (0.15)	1300 (0.15)
Kebumen	Early	932 (0.21)	972 (0.23)	971 (0.24)
	Mid	928 (0.20)	1039 (0.15)	1092 (0.17)
	Late	938 (0.18)	1050 (0.15)	1088 (0.16)
Sukoharjo	Early	967 (0.27)	1109 (0.19)	1159 (0.18)
	Mid	856 (0.29)	1059 (0.21)	1226 (0.14)
	Late	970 (0.33)	1135 (0.24)	1228 (0.18)

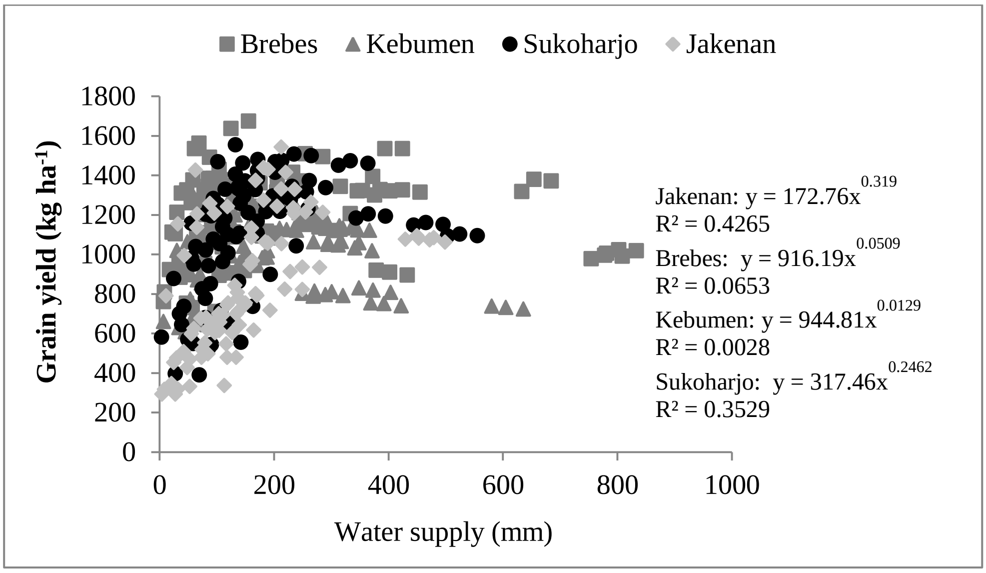

Figure 5: Relationships between water supply (extractible soil water at sowing and rainfall from sowing until maturity) and simulated yield of mungbean at late sowing in loamy soil for four sites (Jakenan, Brebes, Kebumen and Sukoharjo) based on an APSIM scenario analysis using 1983-2013 climate records for each site.

3.4 Mungbean performance at different levels of in-season rainfall

As mungbean relies on soil water content and rainfall over their growing season, it is necessary to evaluate yields at different levels of in-season rainfall (rainfall from sowing to maturity). Data of in-season rainfall were calculated and grouped into 4 levels (0-150; 151-300; 301-450; and 451-600mm) depending on rainfall at each site and the occurrence frequency of each group. At all sites, more than 50% of in-season rainfall ranged from 0 to 150 mm, followed by 20-30% from 151 to 300 mm.

Table 4 shows simulated mungbean yields at different levels of in-season rainfall with regard to sowing time at 70 mm of PAW in loamy soils. Comparing sites at different levels of in-season rainfall, simulated mungbean yields were highest (975 to 1330 kg ha^{-1}) in Brebes and lowest (720 to 1230 kg ha^{-1}) in Jakenan, particularly at the first two levels of in-season rainfall as the occurrence frequency was high. At all sites, simulated mungbean yields at 0 to 150 mm were as high as yields at 151 to 300 mm of in-season rainfall. Low in-season rainfall may be compensated by a good soil type, such as loam with a high PAW (70 mm).

Table 4: Simulated average yield and coefficient of variance (standard deviation/average) for different sowing times (early, mid and late sowing) at 70 mm of PAW in loamy soil at 4 Sites in Central Java in response to in-season rainfall based on APSIM runs from 1983-2013.

Sites	Sowing time	Grain yield (kg ha-1) at			
		<150 mm of rainfall	151-300 mm of rainfall	300-450 mm of rainfall	450-600 mm of rainfall
Jakenan	Early	726 (0.30)	750 (0.25)	859 (0.29)	
	Mid	977 (0.23)	843 (0.11)	1040 (0.00)	
	Late	818 (0.30)	1232 (0.20)	1074 (0.02)	
Brebes	Early	1216 (0.15)	975 (0.09)	509 (0.02)	728 (0.00)
	Mid	1326 (0.16)	1020 (0.12)	947 (0.53)	
	Late	1326 (0.14)	1326 (0.17)	1269 (0.00)	
Kebumen	Early	1115 (0.13)	870 (0.08)	487 (0.04)	
	Mid	1144 (0.12)	856 (0.15)	692 (0.00)	
	Late	1146 (0.11)	1092 (0.19)	891 (0.42)	724 (0.00)
Sukoharjo	Early	1202 (0.15)	1026 (0.21)	795 (0.19)	
	Mid	1233 (0.14)	1126 (0.09)		
	Late	1192 (0.21)	1354 (0.08)	1269 (0.13)	1095 (0.20)

4. Discussions

4.1 Long-term performance of mungbean at various sowing times, soil types and levels of PAW

This simulation study demonstrates the capability of the model to explore the performance of mungbean in rainfed lowland rice-based cropping systems at a range of management practices and agro-climatic conditions on a long-term scale. Soil water is a crucial factor of crop growth and is a decisive parameter in the initialization of the model. Three levels of PAW (10, 40 and 70 mm) represent low, medium and high initial water levels. The model indicated differences of mungbean yields across sites, at different soil types and sowing times at 10 (Figure 2a-d), 40 (Figure 3a-d) and 70 mm of PAW (Figure 4a-d). At all levels of PAW, mungbean yields were highest in Brebes and lowest in Jakenan, but magnitudes differed to a large extend. The yields seem to follow rainfall distribution (Figure 1), particularly yields of mungbean that were sown late. Mungbean grown at this time received rainfall from August to

October. During this period, Brebes experiences the highest rainfall followed by Kebumen, Sukoharjo and Jakenan. Adequate rainfall and stored soil water at sowing may provide good soil moisture conditions and prevent severe water deficits over the mungbean growing season. This ensures better crop establishment and subsequent growth, as well as greater yields. Meanwhile, at all sites, lower yields of mungbean for early and mid-sowing were related to low rainfall during these months, providing less water in the soil, causing poor crop establishment and growth. In addition, the lowest yields of mungbean in Jakenan may be influenced by high temperatures when compared to the other sites. High temperatures can affect photosynthesis rate and increase respiration rates, reducing energy that is needed by crops to grow (Amthor, 1984).

Mungbean is best grown in un-puddled and aerobic soil conditions. It is not surprising that simulated mungbean grown in loamy soil shows higher yields when compared to that of clay and sand at all sites (Table 2). In general, loam soils tend to contain more nutrients, moisture and humus compared to sandy soils. They also tend to be easier to till and have better infiltration rates for water and air than clay soils. Nevertheless, the puddled conditions after rice become a key problem as soil structures are destroyed and organic matter is declined, therefore providing low soil productivity for the following crops (De Datta and Hundal, 1983). The effects of puddled soil are more pronounced on clay and sandy soils due to their lower nutrients content. On puddled soils, the movement of oxygen in water is slower than in air. The supply of oxygen from the air cannot fulfill the oxygen demand of aerobic organisms in the soil. Consequentially, microbial and biochemical systems in soils are changed, inducing a reduction in the oxidation-reduction potential of soil. The alteration of anaerobic to aerobic conditions also influences microbial carbon (C) and nitrogen (N) dynamics, as well as enhancing inorganic N (Fierer and Schimel, 2002). Mungbean grown under such conditions may suffer from nutrient deficiencies and a lack of microorganisms such as rhizobia and mycorrhiza. The saturated soil limits oxygen supply to the germinating seeds and reduces the metabolic processes during crop germination and establishment (Corbineau and Come 1995). In dry soil, seeds may not germinate due to a lack of soil water content that reduce the imbibition rate and delay crop germination and emergence (Bouaziz et al. 1990). Therefore, the success of mungbean establishment and development with regard to soil types and conditions should take sowing time into account.

Sowing time is an important determinant for the success of mungbean production (Kirchhof et al., 2000b). Sowing at an optimal time will ensure high rates of crop establishment and yield. The simulated results show that sowing mungbean late, in August, gives higher yields than early (June) and mid-sowing (July) (Table 2). The late sowing may ensure good crop establishment, as soil is not very wet. Sowing under such conditions may prevent waterlogging, so emergence and root growth is not inhibited (Kirchhof et al., 2000b). As mungbean tends to be grown immediately after rice, the soil is usually still very wet. Common practice means that waterlogging may well impede the root emergence and growth of a great deal of mungbean production in such areas. Furthermore, when puddled soil dries out, it becomes compact and hard. Consequentially, crop establishment and the proliferation of roots through the soil layers become more difficult (Kirchhof et al., 2000b). This results in low plant available water for crops as well as populations that will lead to low yields (Kirchhof et al., 2000a). Sowing time is therefore crucial for good mungbean performance following rice. This should include allowing the soil to dry out sufficiently and avoiding high soil strength (Kirchhof and So, 1996). Various field experiments conducted in East Java have shown varying results: mungbean grown immediately after rice from March to July is likely to succeed, as a long period of rainfall in these sites ensures sufficient root growth and subsoil water. Delaying sowing decreases yields due to excessive drying and a lack of rainfall after sowing (Rahmianna et al., 2000). Interactions between crop growth and prevailing climatic conditions, as well as soil type therefore determine the optimal window for sowing (So and Ringrose-Voase, 1996; Kirchhof et al., 2000b).

The water content status of a soil is crucial for healthy crop growth, particularly for early growth stages, such as sowing and germination (Robertson et al., 2002). Generally, at high levels of PAW, soils become more productive due to more water in the soil. The results show that the yields increased along with an increased level of PAW, for all sowing times and soil types, particularly in clay and loam soils with different magnitudes (Table 2 and 3). The clay soil generally has a greater water holding capacity due to its high percentage of clay content (Rab et al., 2010). Whereas in sandy soil, the advantage of high soil water at sowing may be lost due to its low water holding capacity. Simulation study on chickpea performance indicates that a starting PAW of 100 mm results in a higher probability (80%) of producing yield when compared to the majority of study site yields (Whish et al., 2007). Furthermore, soil water at sowing and sowing date had strong influences in determining yield.

Concerning residue treatments, simulated yields of mungbean were similar between removed and retained residue treatments (data not shown) at all sites. The application of residue after rice did not affect mungbean yields. It is possible that soil conditions combined with residue applications were not suitable for microbial activity, leading to a decreased decomposition rate. The decomposition of crop residue can be affected by soil water content, as soil water decreases; the decomposition rate of residue is reduced due to limited aeration for microbial activity (Yadvinder-Singh et al., 2005). This is consistent with the findings of Rahmianna et al. (2000), who indicated that the effect of residue as mulch on legume germination and establishment in the humid area of East Java can be ignored.

4.2 Mungbean performance at different levels of in-crop rainfall

Looking at the relationship between water supply from sowing to maturity and yield, there was a non-linear relationship between these two variables at all sites (Figure 5). The grain yield of mungbean increased with water supply rates up to 250 mm stagnating at around 800 to 1400 kg ha^{-1}. Additional water does not increase yield. Rainfall may not be well distributed, hence influencing yield.

As the distribution of the first two levels of in-season rainfall (0 to 150 mm and 151 to 300 mm) was higher compared to others, yields were focused at these levels. According to simulation results, yields of mungbean were highest in Brebes (ranging from 975 to 1330 kg ha^{-1}) and lowest (ranging from 726 to 1230 kg ha^{-1}) in Jakenan (Table 4). Simulated yield differed slightly between these two levels of in-season rainfall accumulation. The difference in yields between 0 to 150 mm and 151 to 300 mm ranged from 100 to 300 kg ha^{-1}. Low in-season rainfall is satisfied by a high level of PAW (70 mm) as well as a good soil type (loamy soil). High initial water provides more soil water content at sowing. Loam soils also tend to have a more suitable structure and contain more organic matter to ensure good crop establishment, growth and yield. The performance of mungbean in rainfed lowland rice-based cropping systems can be examined using APSIM. This simulation represents a complex relationship between yield, sowing time, soil type, PAW, crop residue, rainfall and temperature. Interpreting simulation output of water supply for different mungbean cultivars has to be considered so that more detailed information can be gained.

5. Conclusions

The scenario analysis has determined key factors influencing mungbean performance in rainfed lowland rice-based cropping systems in Central Java, Indonesia. The results show that initial water or PAW at sowing, as well as sowing date is crucial in determining mungbean yield. A high level of PAW (70 mm) produced yield of around 1000 to 1200 kg ha^{-1}, which is in the range of actual yields achieved by farmers. Sowing legumes shortly after the rice harvest can impair their germination due to waterlogged conditions, resulting in poor crop establishment and growth. Delaying sowing allows soil to dry to optimum moisture conditions, increasing seedling emergence and root growth, improving crop establishment. In addition, high rainfall following the crop growing period can provide sufficient water for crop growth.

Low rainfall, poor soil moisture and structure in this system will almost certainly reduce yields. Further investigation is required to select specific cultivars for different regions that match rainfall patterns, and to look into how to manage soil structure challenges following rice puddling. Other cropping options that are less affected by soil structure and waterlogging problems should also be investigated.

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IV. Intensification of the fallow phase on rainfed lowland rice and the opportunity to grow pre and post-legume crops in the northeast Thailand: A simulation study

1. Introduction

Thailand is geographically and administratively divided into four regions; central, north, northeast, and south. The northeastern region is situated 90 to 200 m above sea level with an undulating topography (McLean et al., 2003). Almost half of the total rice land in Thailand is located in this region and nearly 5.9 million hectares are used for rainfed rice farming (Haefele et al., 2006). However, the average rice yields in northeast Thailand (1.8 ton ha^{-1}) are the lowest in the country compared to an average of 2.9 ton ha^{-1} in the central region. Infertile sandy soil with low organic matter content, low water holding capacity, and low cation exchange capacity all contribute to such low yields (Wonprasaid et al., 1994; Naklang et al., 1999b). Another factor that poses a constraint to achieving higher yields in this region is high climate variation in terms of both the amount of rainfall and its timing. Annual rainfall varies widely between 1000 and 2000 mm with varied distribution. The delay of the rainy season onset in May and June, the occurrence of dry spells in late June and July and a period of short flooding in September and October contribute to the prominent constraints (Wonprasaid et al., 1994).

In soils of low fertility, amelioration of physical and chemical problems is often achieved via attempts to increase the soil organic matter content. A number of studies in northeast Thailand have shown the benefit of crop residue incorporation on the improvement of organic matter. Long term incorporation of rice straw has increased the fertility and productivity of soil at the Surin Rice Experiment in northeast Thailand (Naklang and Rojanakusol, 1992). Meanwhile, a mixture of groundnut/*Sesbania* with rice straw treatments has improved soil carbon in Khon Kaen, northeast Thailand (Vityakon et al., 2000). However, rice straw characterized by a high C:N ratio and low nutrient content contributes only a little to the availability of sufficient nutrients for the following crops. Green manures such as *Sesbania rostrata* and *Aeschynomene afraspera* with lower C:N ratios (10:1-20:1) seem to be appropriate sources of organic matter in rainfed lowland rice (Gines et al., 1986; Herrera et al., 1989; Vityakon et al., 2000). These legume residues are also able to provide short term benefits, i.e. provision of nutrients, and to improve soil fertility in the long-term by enhancing the capacity of the soil to absorb nutrients, improving soil structure and increasing the microbial activity. As a result of leguminous residue application, rice yields have increased around 20%, and yields have been seen to increase when *Sesbania rostrata* is applied with farm yard manure (FYM) or chemical fertilizer (Herrera et al., 1989).

In rainfed lowland rice areas, legumes may be grown before or after rice crops as a green manure, or most commonly a source of food and fodder that may increase farm income (Buresh and De Datta 1991; Chandrasekaran et al. 1996). Thus, green manures can contribute to the sustainable intensification of rice systems by providing both an increase in soil fertility and farm productivity. In these systems, a single flooded rice crop is generally practiced by farmers because of rainfall as the main source of water prior and during the rice growing season. A second rice crop is likely after the rainy season if there is additional irrigation during key crop growth stages. Unfortunately, the success of the second rice is limited because water is less available, farmers therefore grow dry season crops such as legumes that require less water compared to rice (Garrity and Liboon, 1995; Rahmianna, 2007). The site-specific adapted incorporation of legumes in the lowland rice-based cropping systems, however, is the key challenge. Generally, these crops can be sown at the onset of the rainy season and incorporated before rice planting. Another sowing technique is broadcasting the seed into existing rice stands before harvest or into rice stubble without cultivation. Both establishment techniques are expected to utilize residual soil moisture (Arunin et al., 1994). The main problem in these systems is that the legumes require rain early enough to allow a crop to mature, but not excessive enough to cause waterlogging. Seed germination and emergence is reduced under waterlogged conditions as saturated soil is badly aerated. Consequently, oxygen supply to the germinating seed is limited and metabolic processes during crop germination, establishment and growth is restricted (Corbineau et al., 1995). Such processes are closely determined by the site-specific soil physical properties, in particular soil structure, bulk density and infiltration rate (Garrity and Liboon, 1995). Relay planting is not usually an option because of land preparation for rice planting. Thus, the pre-rice option is very limited. Intercropping is an option but crops will be damaged by the harvesting of rice and waterlogging. Post-rice will depend on the availability of labour. In addition, when the planting of a legume crop is conducted after rice, the crop may experience drought stress during the later growth stages (Buresh and De Datta, 1991). At this stage, the soil water content may deplete and reduce the imbibition rate and delay crop germination and emergence.

Many field experiments have been conducted in northeast Thailand to specify the use of pre and post-legume crops to improve nutrient availability and soil fertility (Herrera et al., 1989; Arunin et al., 1994; Vityakon et al., 2000), but studies that focus on intensifying the fallow phase for fodder or grains are limited. Field experiments seem to be expensive and time consuming, and results obtained from such experiments are limited for a certain period of time (only for 2 or 3 years study) and are insufficient to determine temporal variation linked to climate (Keating et al., 2002). Therefore, the potential success of legumes within a rainfed lowland rice-based cropping system, which include complex interactions between crops, soil, rainfall variation and management, should receive more attention and analysis. Crop simulation models allow these complex interactions to predict and evaluate crop performance (Hoogenboom, 2000; Holzworth et al., 2014), and provide a method to specify both short and long-term agricultural practices with short time requirements and low costs (Malone et al., 2007).

The Agricultural Production System Simulator (APSIM) model is widely used to operate crop, soil and atmospheric interactions in agricultural systems (McCown et al., 1996; Holzworth et al., 2014). The models simulate crop growth and development as well as the soil and plant water and nitrogen (Probert et al., 1998a). APSIM has been parameterized, calibrated and validated for a range of environmental conditions and management options (Holzworth et al., 2006; Holzworth et al., 2014). However, the ability of crop simulation models to predict and evaluate the long-term potential of pre and post-legume crops in rainfed lowland rice areas in northeast Thailand has not been tested. Although APSIM was developed for dryland cropping systems,recently the ORYZA2000 rice model, which was developed by IRRI and Wageningen University (Bouman et al., 2001), has been incorporated into the APSIM framework and validated through various studies (Zhang et al., 2004; Gaydon et al., 2012). ORYZA2000 has become one of the most widely used and tested simulation models for rice. Making such links has enabled APSIM to simulate rice growth and development, addressing N dynamics, crop sequences, intercropping, crop residue and soil management (Zhang et al., 2004). The objective of this study is to: (i) calibrate and evaluate APSIM for simulating a rice based cropping system with pre and/or post rice legume crops using data from the field experiment at the Ubon Rice Research Center (Naklang et al., 1999a); (ii) investigate the long-term potential of intensified rice/or fallows in relation to historical climate data; (iii) specify the potential establishment and productivity of legumes within rainfed lowland rice-based cropping systems in northeast Thailand.

2. Material and methods

2.1 Site description

Data for model calibration and evaluation were derived from field experiments conducted at the Ubon Rice Research Center, in northeast Thailand from 1992 to 1998 (Naklang et al., 1999a). Ubon (15°14’ N, 104°50’ E) receives an average annual rainfall of 1610 mm, and experiences an average minimum temperature range of 17.7 to 24.5^{o}C with the lowest values from December to January (Table 1).

Table 1: Average monthly radiation and rainfall, and monthly max and min daily temperatures based on daily weather records from 1983 to 2013 at the Ubon Rice Research Center weather station.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Radiation (MJ m^{-2})	574	569	651	646	613	534	550	522	507	544	528	532	6671
Rainfall (mm)	3	15	33	91	227	220	265	305	314	121	22	6	1610
Max average daily temperature (^{o}C)	31.9	34.1	35.7	36.4	34.7	33.3	32.6	32.0	31.8	31.8	31.5	30.7	33.0
Min average daily temperature (^{o}C)	17.7	20.0	22.4	24.3	24.5	24.5	24.2	24.0	23.7	22.4	20.4	17.9	22.2

2.2 Description of measured field data set collected 1992-1998

The field experiments were conducted from 1992 to 1998 at the Ubon Rice Research Center, in northeast Thailand (Naklang et al., 1999a). The soil is an acid sandy soil (*Aeric Paleaquult*) of the Roi Et series (a widely distributed soil for the production of rice in northeast Thailand) containing 85.4% sand, 10.5% silt, and 4.1% clay, with a pH (in water) of 4.2. The experiment site was cleared in 1971 and farmed to rice for at least 20 years prior to the experiment.

The treatments were laid out in a complete factorial design consisting of three rice-based cropping systems (rice alone, rice with mungbean/cowpea (*Vigna radiata/Vigna unguiculata*) and rice followed by cowpea (*Vigna unguiculata*)) by two leaf litter rates

(0 and 750 kg ha^{-1} of *Samanae saman* leaves), two fertiliser rates (18, 14, 13 and 50, 14, 13 kg ha^{-1} of NPK) and two crop residue treatments (rice stubble removed and returned), with 3 replications. The sowing and harvesting dates of rice and legume crops from 1992 to 1998 are described in detail in Naklang et al. (1999a).

The dry leaves of rain trees were applied and incorporated into the soil one week before the rice was sown. The fertiliser was applied and incorporated into the soil at planting in 1992, 1993 and 1995 with low (0, 14, 13 kg ha^{-1} of NPK) and high (32, 14, 13 kg ha^{-1} of NPK) rates of fertiliser treatments. Meanwhile, in 1994 and 1996-1998, fertiliser was broadcasted one month after planting. A second fertilizer application was top-dressed at panicle initiation to all plots at the rate of 18 kg ha^{-1} of urea.

Rice (cv. RD 15) was broadcasted onto cultivated moist soil in all cropping systems. In the rice with mungbean/cowpea system, the legume seeds were broadcasted together with the rice. The rice and legumes grew together until the legume could no longer tolerate the anaerobic conditions. In the rice followed by cowpea system, cowpea (cv. CP4-3-2-1) was sown 10 days after harvesting the rice at a 20 x 40 cm spacing. When the crop matured, it was harvested and separated into shell and seed. After all crops stopped producing seeds, the leftover biomass was weighed and restored to its respective plot along with the shells.

Rice crops were harvested at maturity and crop samples were measured for the nutrient analysis of grain, threshed panicle straw, and stubble. In the removed stubble treatments, the straw was removed from the stubble, while it remained in the stubble for the retained treatments. Soil sampling was taken from the layers 0-10 cm following the harvest and prior to the cultivation of the following crop. Soil samples were then dried at 40 °C and ground for analysis.

2.3 Parameterisation of the APSIM model

In this study, APSIM version 7.5 was set up with rice and cowpea module, the soil water module (SOILWAT), the soil N module (SOILN), residue module (Surface OM), and Manager. The APSIM model was calibrated for rice and cowpea crops grown from 1992 to 1993 at the Ubon Rice Research Center, in northeast Thailand.

2.3.1 Soil setups

The SOILWAT and SOILN modules were parameterised following standard practices using APSIM. The input parameters were estimated from soil characterization data by Konboon et al. (1999) and Naklang et al. (1999). For the SOILWAT module the parameters include soil bulk density, saturated soil water content, drained upper limit water content at field capacity (DUL) and crop lower limit (Table 2). The two parameters (U and CONA) that determine the first and second stage of soil evaporation were set to 4 and 2 mm day^{-1} respectively. Runoff is linked to the setting of the USDA curve number and was set as 68. The fraction of water drained to the next soil layer under saturated conditions per day (SWCON) is 0.7 for all layers following standard parameterisation for a sandy soil. This condition allows to pond water when its rice as the drainage is much slower after rice due to puddling. For soil water content below DUL, water movement relies on the gradient of the water content between adjacent layers and the soil's diffusivity, defined in APSIM as diffusivity constant and diffusivity slope. The default values of 250 (diffusivity constant) and 22 (diffusivity slope) were used to reflect a sandy soil.

The parameters for SOILN module include organic carbon (OC), pH, Finert (inert C fraction) and Fbiom (microbial biomass fraction) are presented in Table 2. Finert and Fbiom, the different pools of the organic matter are based on typical default values representing the fraction of the total organic carbon in the specific pool (Luo et al., 2014). The initial nitrogen content in the soil was set to 6 and 4 kg ha^{-1} of NO_3, and 4 and 1 kg ha^{-1} of NH_4 at 0-20 and 20-200 cm respectively. Initial water content at sowing was set to 100 % evenly distributed.

Table 2: Soil Bulk density (BD), saturation (SAT), lower limit of plant-available water (LL15), drained upper limit of water (DUL), organic carbon (OC), fraction of active soil organic material as microbial biomass (Fbiom) and fraction of inert organic matter (Finert) at various soil depths for the initiation of the APSIM model.

Depth (cm)	BD (g cm^{-3})	SAT (mm mm^{-1})	DUL (mm mm^{-1})	LL15 (mm mm^{-1})	SWCON (0-1)	OC (%)	Fbiom	Finert
0-15	1.47	0.38	0.19	0.05	0.70	0.35	0.05	0.40
15-30	1.47	0.38	0.19	0.05	0.70	0.30	0.03	0.60
30-60	1.50	0.36	0.18	0.06	0.70	0.20	0.02	0.80
60-90	1.50	0.35	0.17	0.06	0.70	0.20	0.02	1.00
90-120	1.55	0.35	0.16	0.07	0.70	0.20	0.01	1.00
120-150	1.55	0.35	0.16	0.07	0.70	0.20	0.01	1.00
150-180	1.55	0.35	0.16	0.07	0.70	0.20	0.01	1.00

2.3.2 Plant module calibration

The local rice variety of RD15 was calibrated using the IR72 standard crop parameters (Bouman et al., 2001) according to the procedure explained by Bouman and Van Laar (2006). Data of the rice only cropping system in 1992-1993 was used to parameterize the rice module. Phenological parameters were derived based on the recorded dates of establishment, flowering and physiological maturity phase in the field experiment. Details of phenological parameters are given in Table 3. The parameter values were adjusted until simulated phenological development phase values best fit with measured values.

Table 3: Phenological parameters and values for the RD15 variety.

Parameters	IR72 (Default values)	RD 15 values	Units
Development rate in juvenile phase	0.000773	0.000559	$^{o}Cd^{-1}$
Development rate in photoperiod-sensitive phase	0.000758	0.000469	$^{o}Cd^{-1}$
Development rate in panicle development phase	0.000784	0.000359	$^{o}Cd^{-1}$
Development rate in reproductive phase	0.001784	0.001880	$^{o}Cd^{-1}$

Parameterisation of the cowpea was limited by a lack of field observations, which is why the default values of the cowpea cv. Banjo were used (Table 4.)

Table 4: Phenological parameters and values for Banjo variety.

Acronym	Parameters	Banjo values	Units
y_hi_incr	Rate of harvest index	0.014	1/day
tt_emergence units	TT from emergence to end of juvenil phase	552	$^{o}Cd^{-1}$
x_pp_end_of_juvenille description	Photoperiod	13.3	H
y_tt_floral_initiation units	TT from initiation to flowering	20	$^{o}Cd^{-1}$
y_tt_flowering units	TT from flowering to start grain fill	100	$^{o}Cd^{-1}$
y_tt_start_grain_fill units	Start grain fill to end grain fill	280	$^{o}Cd^{-1}$
tt_maturity units	TT from maturity to harvest ripe	5	$^{o}Cd^{-1}$

2.4 Model performance analysis

The first two years of the field experiment were used for the calibration and excluded from the evaluation of the model afterwards. The evaluation of the model was performed on the 2 cropping systems (rice only and rice followed by cowpea cropping systems) with eight treatments and five years of experimentation for rice phenology, rice grain yield and biomass, and cowpea yield. Observed and simulated paired-values of parameters were graphically compared and statistically analyzed using linear regression. The comparison determined the slope (α), intercept (β) and coefficient of determination (R^2) of the linear regression. The root mean square error (RMSE) was predicted between observed and simulated paired-values to quantify the goodness of fit for these comparisons. The efficiency of forecasting (EF) was also used to evaluate the performance of the model (Loague and Green, 1991). The equation of RMSE and EF (Eq. (1) and Eq. (2)) is follows:

$$\text{RMSE} = [(\sum (O - P)^2/n)]^{0.5} \qquad (1)$$

$$\text{EF} = 1 - [(\sum (O - P)^2) / (\sum (O - \bar{O})^2)] \qquad (2)$$

Where O and P are the paired observed and simulated values, $\bar{O}$ is the mean of all observed values and n is the total number of observations. The good model performance is indicated by the low values of RMSE (close to 0), while the poor model performance is indicated by the high values of RMSE. The values of EF describe the overall goodness-of-fit of the data with values close to one indicating high model performance, and negative values indicating poor performance (Mayer and Butler, 1993). In addition, the probability of each outcome of pre and post-legume crop practices were evaluated using cumulative distribution functions (CDF).

2.5 Scenario analysis

Crop model simulations were developed to evaluate the probability of cowpea performance at two planting systems (before and after rice crop) under rainfed conditions in Ubon, northeast Thailand. These systems were examined using climate data from 1983 to 2013. Details of scenarios are describes as follows:

(i) Planting time for rice: sowing date was fixed to 17th June. Rice cultivar of RD15 was directly sown at a density of 125 plants m^{-2}.

(ii) Planting time for cowpea pre-rice: sowing dates were fixed to 1st February for the early, 1st March for the medium, and 1st August for the late sowing time. The cowpea cultivar Banjo was directly sown at a density of 20 plants m^{-2}.

(iii) Planting time for cowpea post-rice: sowing dates were fixed to 22nd November for the early, 6th December for the medium, and 20th December for the late sowing time. Cowpea cultivar Banjo was also directly sown at a density of 20 plants m^{-2}.

(iv) Plant available water (PAW), specifies the water available to the plant: six values of PAW were set from 0 to 192 mm at an interval of 38 mm of water for the soil. These values are considered to represent low, moderate and high PAW.

(v) Fertiliser treatment: two fertiliser rates (18, 14, 13 and 50, 14, 13 kg ha^{-1} of NPK) were applied for rice, while cowpea did not receive any fertiliser.

All scenarios above were arranged using the interface of APSIM's Manager and the SoilWat module. Simulations began on the 1st of July 1983 and ran until the 31st of December 2013. Soil water, soil mineral N and soil organic matter were reset to initial conditions.

3. Results

3.1 Parameterisation of the APSIM for the local rice variety

The APSIM-Oryza was parameterized for the local rice variety RD15 using parameterized local soil (Table 2). The parameters were derived based on the phenology of RD15 at different growth stages and are presented in Table 3.

3.2 Evaluation of the APSIM model

The model was evaluated for rice phenology, rice grain yield and biomass as well as cowpea grain yield. Model performance on simulating rice phenology is presented in Figure 1. The correlation between observed and simulated values of the development stages of the crop was good (R^2: 0.99 and RMSE: 3.79) because of the calibration. The simulated values of development stages of rice were similar for all treatments. Data from field experiments was comprised of a range of rice grain yield (1598-2984 kg ha^{-1}) and biomass (5075-9790 kg ha^{-1}) over 5 years (Figure 2a-b). As the simulated values of grain yield and biomass of rice do not showing differences in leaf litter and residue treatments, the average of these treatments are presented.

The simulation of grain yield was generally fair with a RMSE of 717 kg ha^{-1} compared to an average of observed yields of 2397 kg ha^{-1} (Figure 2a). The simulation of biomass was generally much better with an RMSE of 1296 kg ha^{-1} against an average of 7163 kg ha^{-1} (Figure 2b). The RMSEn in % of the observed mean was 29.9 for grain yield and 18.1 for biomass predictions with a good EF (Table 5). This indicated that the APSIM model was able to predict grain yield and biomass based on model efficiency.

Table 5: Statistical criteria (root mean square error, RMSE and model efficiency, EF) as well as observed range and mean for evaluating total biomass and grain yield of rice.

Parameters	N	Observed range (kg ha^{-1})	Observed mean (kg ha^{-1})	RMSE	RMSEn (%)	EF
Rice grain yield	20	1598-2984	2397	717	29.9	0.65
Rice biomass	20	5075-9790	7163	1296	18.1	0.79

The fertilizer treatments had a significant influence on the rice grain yield and biomass. Rice grain yield and biomass were higher at high fertilizer rates. The response of rice yield and biomass accumulation to low and high fertilizer rates was realistically predicted by APSIM. The cropping systems, however, did not influence rice grain yield and biomass. Rice grain yield and biomass between rice only and rice followed by cowpea cropping systems were similar, which is in line with the results from field experiments particularly at high fertilizer rates. In general, the response of rice yield and biomass to different cropping systems was simulated well by the model. In the field experiments, the application of a small amount of leaf litter increased rice grain yield in 1994 and 1996 to 1998. However, the retention of rice straw did not have effect on grain yield until 1998 (Naklang et al., 1999a). The simulations were not able to represent these subtle differences caused by small but long-term additions of leaf litter or residues. The low C:N ratio of leaf litter decomposed residue too slowly during the simulation. In the APSIM model, litter quality is incorporated by changing the specific decomposition rate (k) as a function of litter type and the initial residue of C:N ratio (Probert et al., 1998b). It is possible that the C:N ratio factor did not sufficiently describe the impact of the litter or residue quality on decomposition.

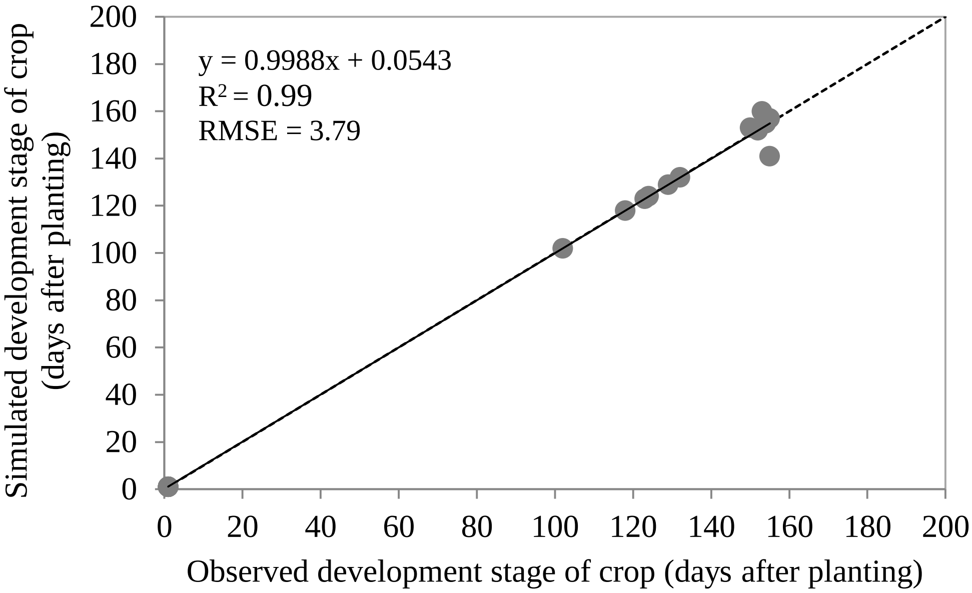
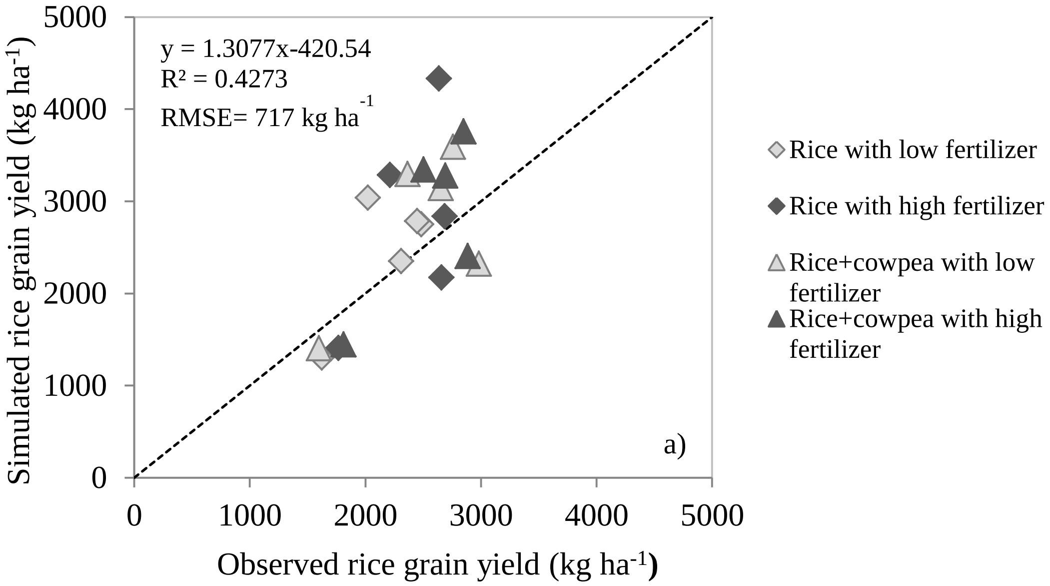


Figure 1: Observed versus simulated development stage of crop. The dotted line represents the 1:1 line. The straight line represents the regression line forced through the origin.



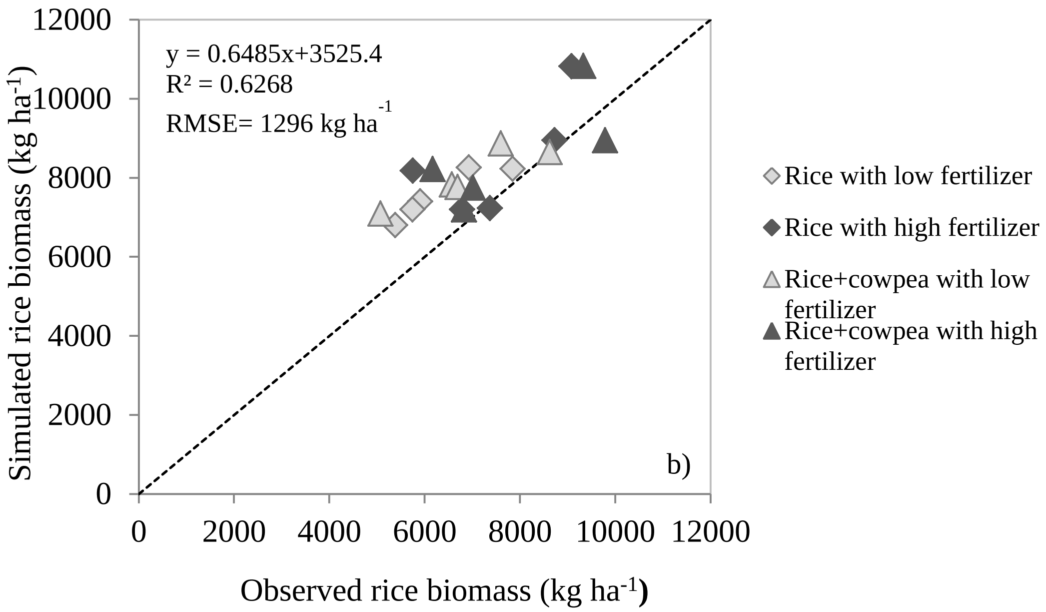


Figure 2a-b: Observed versus simulated (a) rice yield and (b) biomass at harvest for two cropping systems (rice only and rice followed by cowpea) and fertilizer treatments (low and high rates). The dotted line represents the 1:1 line.

Observed and simulated cowpea grain yield after rice cropping for the period 1995 to 1998 are presented in Table 6. The simulated values of grain yield were underestimated by APSIM. Simulating indeterminate legumes is difficult, especially for grain yields of less than 0.6, and usually less than 0.25 t ha^{-1}. For indeterminate legumes such as cowpea, partitioning of assimilates to grain during the grain-filling phase should carefully represent the gradually increasing demand of new flowers and fruits. The seed number, however, is species-specific and continually changing during the period of pod setting (Turpin et al., 2002). Therefore, it is challenging to capture the proper partitioning of assimilates.

Table 6: Observed and simulated cowpea grain yield after rice cropping from 1995 to 1998.

Year of experiments	Grain yield (kg ha^{-1})			
	Observed	Simulated	RMSE	RMSEn (%)
1995	321.1	128.0	244.2	76
1996	162.5	261.8	118	73
1997	442.8	410.8	319.28	72
1998	163.9	118.1	123.11	75

3.2 Scenario analysis

3.2.1 The opportunity of cowpea performance before rice cropping

Selection of sowing time for cowpea before rice was set to 1st February for the early, 1st March for the medium, and 1st April for the late sowing. Sowing cowpea before February led to very low yields, while sowing cowpea after April did not allow sufficient time for the crop to mature before the following rice season. Therefore, three sowing times (February, March and April) had been selected in this study. As soil water plays a role in the establishment and growth of cowpea, six values of PAW were set from 0 to 192 mm for the soil in this simulation.

The scenario analysis showed the impact of sowing time and PAW on the accumulation of grain yield and biomass of cowpea. Sowing time influenced the grain yield and biomass of cowpea (Table 7). Late sowing in April was favorable when compared to early and mid-sowing. The in-season rainfall for the late sowing was 302 mm, considerably higher compared to early and mid-sowing, reflecting a better use of in-season rainfall during the crop growing period. There was a consistent trend of larger soil water used by crops with the larger PAW for all sowing times. The lower PAW appeared to potentially limit soil water used by the crop (the sum of in-season rainfall plus soil water depletion) and reduce cowpea grain yield and biomass. For the late and mid sowing, soil water used by the crop was mainly low compared to the rainfall during the cowpea growing period with an exception with high PAW. The rainfall was almost completely able to meet the crop water requirement and the use of stored soil water was limited. For the early sowing, soil water used by the crop was high compared to the rainfall during the cowpea growing period, indicating that the crops have to depend more on water stored in the soil.

A comparison of variability in grain yields and biomass of cowpea for the early, mid and late sowing times can be evaluated through the cumulative distribution functions shown in Figure 3a-b. With high PAW (192 mm), 40% of seasons with early sowing resulted in yields <400 kg ha^{-1} and 80% <307 kg ha^{-1}, whereas for the mid and late sowing 50% of the spread of yields were <437 and <706 kg ha^{-1}, respectively (Figure 3a). For the early sowing date, biomass varied between 1199 and 2582 kg ha^{-1}, indicating that there were fewer years with rainfall that may support biomass above 2582 kg ha^{-1} (Figure 3b). The low and moderate PAW showed similar trends to that of the high PAW, but magnitudes differed to a large extend (data not shown).

When comparing the simulated grain yields to water supply (the sum of extractible soil water at sowing plus rainfall from sowing until maturity), there was a strong correlation between grain yield and water supply for the early and mid-sowing dates, whereas for the late sowing date the correlation was weak (Figure 4). The grain yield increased along with the increase in water supply for all sowing times with different magnitudes. The yield of cowpea for the early and mid-sowing was highly responsive to water supply, a key driver of grain yield. In years where the water supply was 250 mm or above, yields were 493 and 468 kg ha^{-1}, respectively. Moreover, for the mid sowing date, yields were above 698 kg ha^{-1}, but only in years where the water supply was 450 mm or above. For the late sowing date, the grain yield of cowpea increased with 450 mm of water supply but stagnated around a level of 745 to 750 kg ha^{-1}, depending on the PAW. The response of cowpea to the amount of water supply may have been due to a better use of soil moisture, particularly for the early sowing date that received a relatively low amount of rainfall.

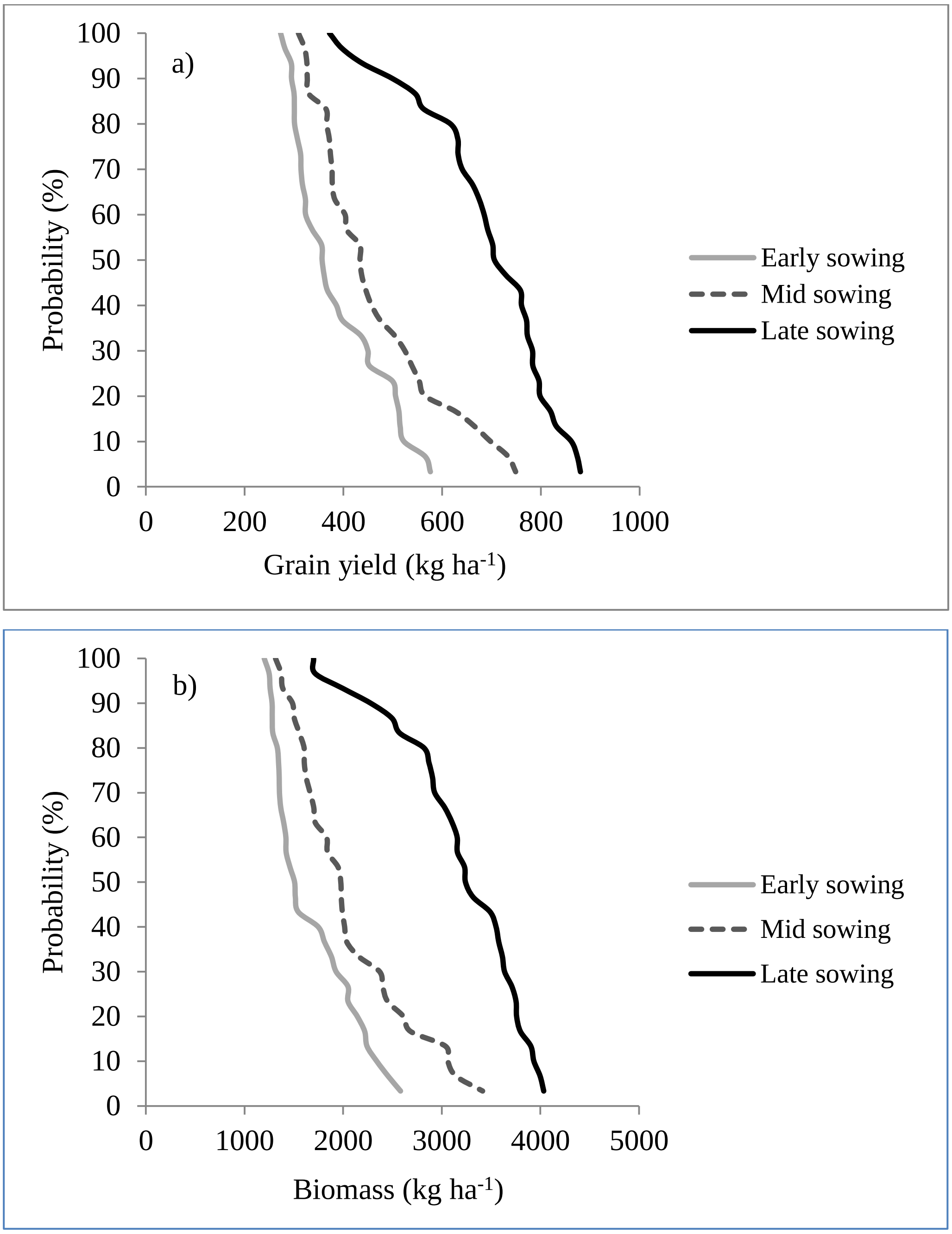


Figure 3a-b: Probability of exceedance APSIM simulations for a) grain yield of cowpea and b) biomass of cowpea (kg ha^{-1}) before rice cropping at the early, mid and late sowing dates at 192 mm of PAW across the 1983-2013 climate record for the Ubon site.

Table 7: Simulated in-season rainfall, soil water used by crop, grain yield and total biomass of cowpea before rice cropping. The simulation scenario using APISM is based on three sowing times, early, mid and late, and six levels of PAW. Mean (n=30) and standard deviation (in brackets) are presented.

Sowing time	PAW (mm)	In-season rainfall (mm)		Soil water depletion[a] (mm)		Soil water used by crop (mm)		Grain yield (kg ha^{-1})		Biomass (kg ha^{-1})	
Early	0	53	(45)	-11	(23)	42	(23)	76	(131)	335	(567)
	38	53	(45)	2	(15)	55	(15)	149	(107)	667	(451)
	77	53	(45)	18	(15)	71	(15)	215	(112)	959	(461)
	115	53	(45)	32	(17)	85	(17)	276	(111)	1222	(457)
	154	53	(45)	47	(16)	100	(16)	334	(103)	1457	(441)
	192	53	(45)	62	(14)	115	(14)	385	(94)	1668	(416)
Mid	0	123	(83)	-63	(61)	60	(61)	322	(240)	1479	(1116)
	38	123	(83)	-21	(39)	102	(39)	259	(140)	1157	(633)
	77	123	(83)	-7	(40)	116	(40)	324	(143)	1443	(643)
	115	123	(83)	7	(40)	130	(40)	379	(139)	1683	(629)
	154	123	(83)	21	(36)	144	(36)	424	(134)	1881	(602)
	192	123	(83)	39	(31)	162	(31)	462	(128)	2050	(574)
Late	0	302	(117)	-134	(69)	168	(69)	616	(146)	2854	(687)
	38	302	(117)	-91	(52)	211	(52)	573	(175)	2651	(819)
	77	302	(117)	-75	(46)	227	(46)	623	(167)	2878	(786)
	115	302	(117)	-53	(39)	249	(39)	658	(157)	3037	(742)
	154	302	(117)	-23	(31)	279	(31)	679	(145)	3131	(693)
	192	302	(117)	7	(27)	309	(27)	689	(137)	3176	(654)

[a] soil water depletion: difference between extractible soil water at sowing and harvest

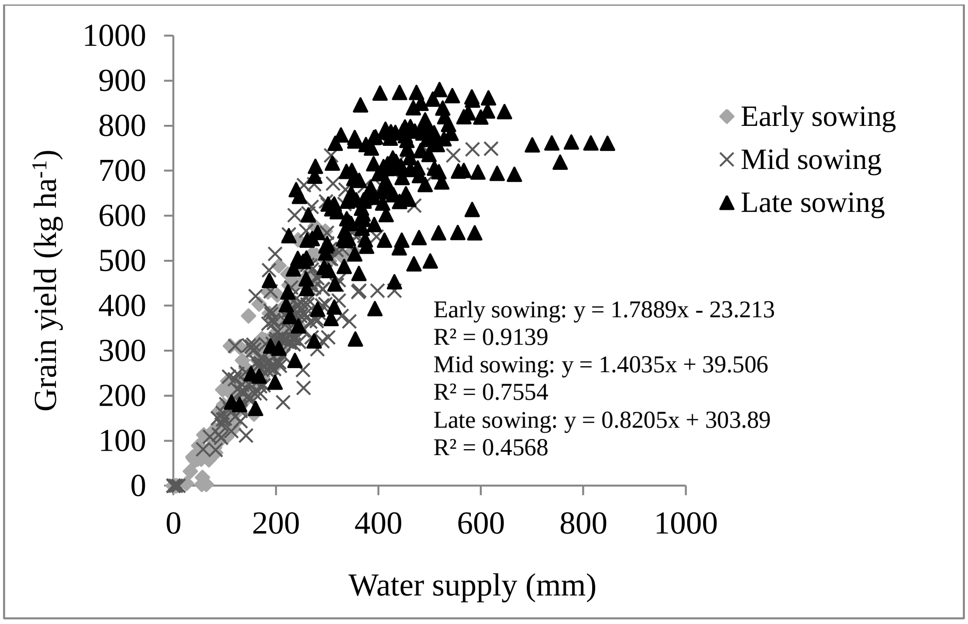


Figure 4: Relationships between water supply (extractible soil water at sowing plus rainfall from sowing until maturity) and simulated yield of cowpea before rice cropping for early, mid and late sowing dates at six levels of PAW based on an APSIM scenario analysis using the 1983-2013 climate record for the Ubon site.

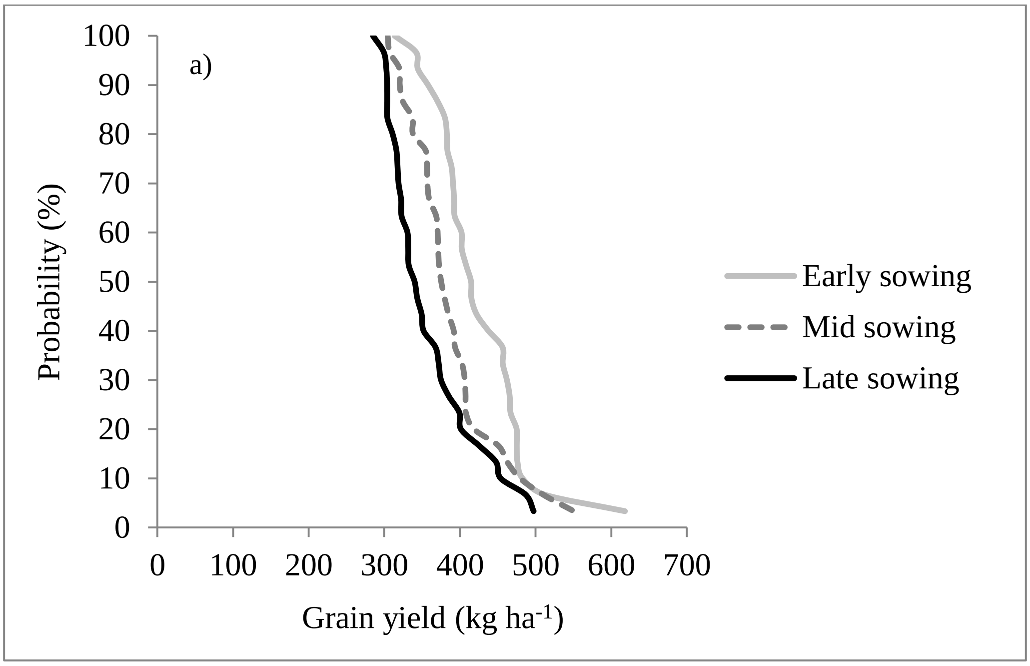
3.2.2 The opportunity of cowpea performance after rice cropping

Selection of sowing time for cowpea after rice was set to 22nd November for the early, 6th December for the medium and 20th December for the late sowing dates. Six values of PAW were also set from 0 to 192 mm for the soil in this simulation.

The scenario analysis demonstrated the impact of sowing time and soil water on the accumulation of grain yield and biomass of cowpea. Sowing time and plant available water influenced the grain yield and biomass of cowpea (Table 8). Early sowing immediately after the rice harvest in November was favorable against the mid and late sowing dates. The simulated in-season rainfall showed a relatively low amount of rainfall during the cowpea growing period (Table 8). Similar to the performance of cowpea before rice cropping, there was a consistent trend of higher soil water use with the larger PAW for all sowing dates. The higher PAW appeared to allow more soil water to be used by the crop, which increased cowpea grain yield and biomass. For all three sowing dates, soil water used by the crop was mostly higher compared to the rainfall during the cowpea growing period. The rainfall was not able to meet the crop water requirement. Therefore, crops entirely relied on stored soil water to meet their water requirement.

A comparison of variability in grain yields and biomass of cowpea for the early, mid and late sowing dates are given in Figure 5a-b. At the high PAW (192 mm), 40% of seasons for the early sowing date resulted in yields <440 kg ha^{-1} and 80% <383 kg ha^{-1}, whereas for the mid and late sowing dates 50% of the spread of yields was <375 and <340 kg ha^{-1}, respectively (Figure 5a). The biomass varied for the early sowing dates and has a broader spread between 1332 and 2126 kg ha^{-1}, indicating more years with higher rainfall that could support biomass production to 2126 kg ha^{-1} (Figure 5b). The variability of grain yields and biomass for the low and moderate PAW was similar to those with a high PAW (data not shown).

There was a clear trend of increased yield with increased water supply for all sowing dates, but the magnitudes among these dates differed to a large extent (Figure 6). Cowpea yield was favorably responsive to water supply and an increase in water supply boosted the grain yield. For the early, mid and late dates, in years with a water supply of 200 mm or less, the yields obtained were 375, 338 and 303 kg ha^{-1}, respectively. In wet years with a water supply of 300 mm or less, the grain yields for the early sowing date out yielded the mid and late sowing dates with 475 kg ha^{-1}.



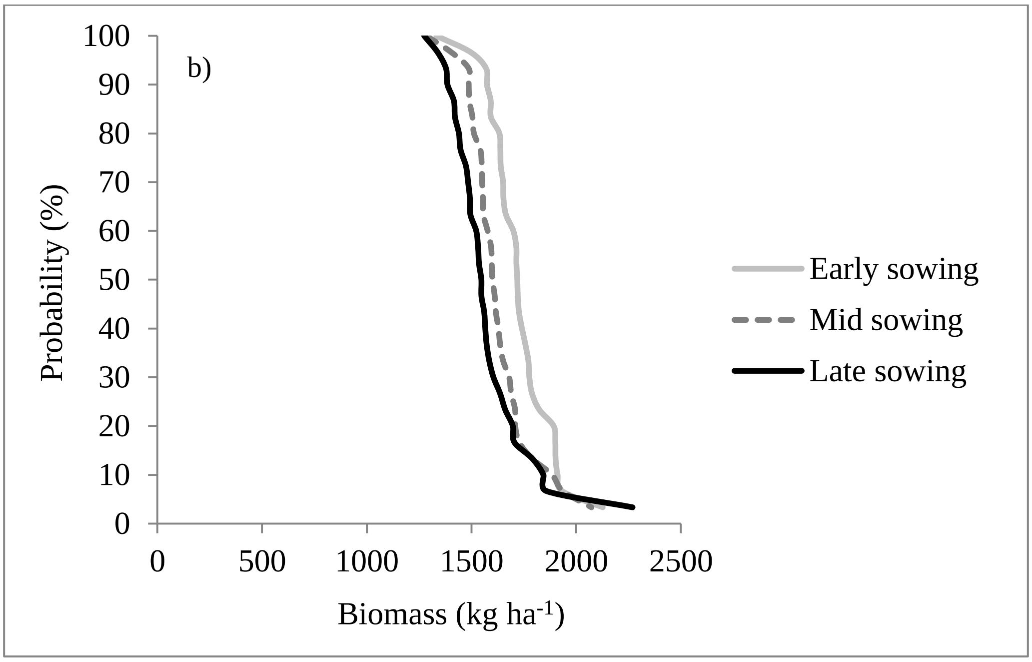


Figure 5a-b: Probability of exceedance APSIM simulations for a) grain yields and b) biomass of cowpea (kg ha^{-1}) after rice cropping at the early, mid and late planting dates at 192 mm of PAW across the 1983-2013 climate records for the Ubon site.

Table 8: Simulated in-season rainfall, soil water used by crop, grain yield and total biomass of cowpea after rice cropping. The simulation scenario using APISM based on three sowing dates, early, mid and late as well as six levels of PAW. Mean (n=30) and standard deviation (in brackets) are presented

Sowing time	PAW (mm)	In-season rainfall (mm)		Soil water depletion[a] (mm)		Soil water used by crop (mm)		Grain yield ($kg\ ha^{-1}$)		Biomass ($kg\ ha^{-1}$)	
Early	0	10	(24)	-3	(11)	7	(27)	16	(58)	75	(250)
	38	10	(24)	17	(14)	27	(24)	106	(75)	502	(296)
	77	10	(24)	32	(14)	42	(23)	181	(75)	843	(257)
	115	10	(24)	48	(15)	58	(21)	259	(71)	1165	(212)
	154	10	(24)	63	(13)	73	(20)	336	(65)	1445	(174)
	192	10	(24)	78	(18)	88	(23)	423	(61)	1722	(153)
Mid	0	9	(20)	-3	(11)	6	(12)	2	(10)	10	(46)
	38	9	(20)	12	(11)	21	(12)	83	(30)	400	(94)
	77	9	(20)	28	(12)	37	(12)	152	(39)	730	(112)
	115	9	(20)	45	(12)	54	(12)	225	(47)	1046	(127)
	154	9	(20)	60	(12)	69	(12)	301	(53)	1332	(140)
	192	9	(20)	74	(12)	83	(12)	386	(58)	1621	(156)
Late	0	16	(30)	0	(3)	16	(29)	5	(16)	24	(76)
	38	16	(30)	9	(18)	25	(19)	83	(37)	407	(148)
	77	16	(30)	25	(18)	41	(19)	146	(44)	720	(164)
	115	16	(30)	41	(19)	57	(19)	215	(49)	1021	(174)
	154	16	(30)	56	(18)	72	(19)	282	(54)	1294	(183)
	192	16	(30)	70	(18)	86	(19)	357	(57)	1569	(192)

[a] soil water depletion: difference between extractible soil water at sowing and harvest

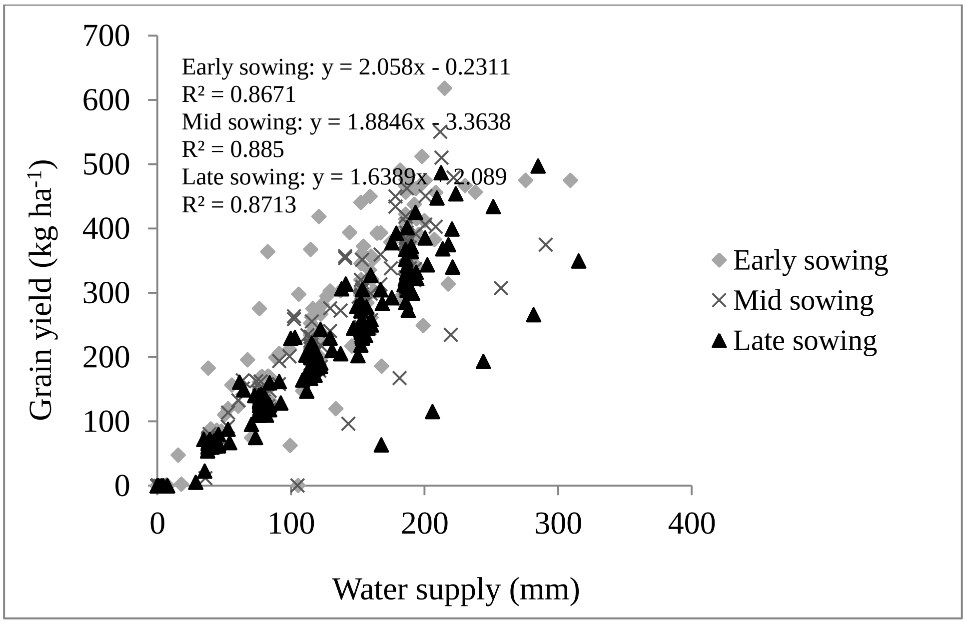


Figure 6: Relationships between water supply (extractible soil water at sowing plus rainfall from sowing until maturity) and simulated yield of cowpea after rice cropping for early, mid and late planting dates at six levels of PAW based on an APSIM scenario analysis using the 1983-2013 climate records for the Ubon site.

4. Discussions

4.1 Model performance

The performance of rice cv. RD15 on the rice legume cropping system had been parameterized and evaluated using data from the field experiment at the Ubon Rice Research Center in northeast Thailand (Naklang et al., 1999a). Model parameterisation had modified parameters in order to carefully simulate rice variety performance that requires a specific time for maturity (Table 3). The results of this study demonstrated that the APSIM-ORYZA performs well in simulating the dynamics of rice phenology for all treatment conditions, as evaluated through comparison and goodness of fit parameters (Figure 1). The strong correlation between observed and simulated development stages of the crops is due to the parameters being derived from the observed phenology.

The model could demonstrate 42.7% of the variation in rice grain yield and 62.7% of the variation in rice biomass caused by treatment applications and inter-annual climate variations (Figure 2a-b). The fair fit of the dynamics of rice grain yields and biomass is probably due to low crop responsiveness in relation to the applied treatments, in particular the leaf litter and residue treatments. The leaf litter and residue treatments did not have influence on simulated grain yield and biomass, whereas in the field experiments, the application of leaf litter impacted rice grain yields. The simulation cannot capture the subtle differences caused by small but long-term additions of leaf litter or residues. Simulation studies on sugar cane residues showed that the residue decomposition rate was influenced by initial mass of residue (Thorburn et al., 2001). After 100 days of incubation, the simulated residue mass of sugar cane was much lower than observed, where the initial mass of residue of less than 5-7 ton ha-^{1} was applied. In this simulation, the small amount of leaf litter (750 kg ha^{-1}) with a low C:N ratio resulted in a slow decomposition rate, delaying the mineralization of N, which is required for crop growth. In the APSIM model, the specific decomposition rate (k) as a function of litter type and the initial residue of the C:N ratio may be crop-specific (Probert et al., 1998b, Thorburn et al., 2001). The impact of the leaf litter quality on decomposition could not be adequately explained by the C:N ratio factor.

The APSIM-ORYZA generally predicted rice grain yield and biomass to a high level of accuracy in response to fertilizer treatments. Similar results of the capability of the model to simulate rice variables, such as grain yield and biomass, were also observed by Gaydon et al. (2009) and Zhang et al. (2007). Simulated grain yield and biomass followed the pattern of observed values, although simulated values were higher than the observed ones. Grain yields and biomass accumulation increased along with higher N fertilizer rates. Increases in simulated grain yields can be related to higher N uptake as N rates increased. Unfortunately, there was no data on N uptake from the field experiment to support this simulation. The simulation of grain yields and biomass indicated a RMSEn prediction of 18 and 30%, respectively. According to Jamieson et al. (1991) this RMSE is considered fair, indicating that the capability of the model to simulate rice grain yield and biomass under non-limiting nutrient conditions requires further evaluation.

For cowpea, the APSIM model could not captured the dynamics of grain yields and biomass well, as evaluated by a high RMSE (Table 5). Data from the field experiments was very limited, and the default variety of cowpea used in this study (cv. Banjo) could not represent the local variety. There are studies describing the calibration and validation of APSIM for mungbean, peanut, chickpea, lucerne (Robertson et al., 2002), and fababean (Turpin et al., 2002) over a range of management and climatic conditions. Unfortunately, there are no papers explaining the validation of APSIM for cowpea. Assimilates partitioning to the grain of legumes is driven by daily rate of harvest index (HI), which is cultivar specific (Robertson et al., 2002), and is usually analysed with a linear increase in HI during grain-filling. The demand of assimilates increases over each day of grain-filling by a set fraction. For indeterminate legumes and cultivars such as cowpea, assimilates partitioning to the grain during the grain-filling phase requires carefully represent the gradually increasing demand of new flowers and fruits (Turpin et al., 2002). The HI technique is therefore challenging because the seed number is continually changing during the period of pod-setting, resulting in difficulties in the application of a seed growth rate to a predicted seed number. The model is not yet able to simulate the indeterminate habits of cowpea under this rice-legume cropping systems, but this may be a useful aspect for research with a focus on indeterminate cultivars.

4.2 Scenario analysis

The aim of the scenario analysis was to evaluate the probability of cowpea performance at two planting systems (before and after a rice crop) under rainfed conditions in Ubon, northeast Thailand. The APSIM model demonstrated continuous simulations of soil conditions and rice legume crop sequences with different planting dates of cowpea. As presented in Table 7, the model demonstrated that mean grain yields and biomass of cowpea before rice cropping differed with sowing time and PAW level. At the highest PAW, delay of sowing in April gave high grain yields and biomass with 50% of the spread from 706 and 3241 kg ha^{-1}, respectively (Figure 3a-b). At the low PAW, particularly in the sandy soils, the water can be easily lost through drainage, especially under high rainfall conditions (Sadras et al., 2003), resulting in less water stored and lower grain yields and biomass. Therefore, sowing cowpea during the dry season before rice cropping is likely a result of rainfall, which was higher in April than February and March (Table 1 and 7), leading to higher grain yields and biomass production.

The amount of soil water used by the crop was also related to grain yields and biomass production. For the early sowing date, depending on the PAW, cowpea used 42-115 mm of water with mean grain yields ranging from 76 to 385 kg ha^{-1} and biomass ranging from 335 to 1668 kg ha^{-1}. For the mid sowing date, the water used was 60-162 mm with mean grain yields and biomass ranging from 322 to 462 kg ha^{-1} and 1479 to 2050 kg ha^{-1}, respectively (Table 7). For the late sowing date, the amount of soil water used by the crop was 168-309 mm with main grain yields and biomass production ranging from 616 to 689 kg ha^{-1} and 2854 and 3176 kg ha^{-1}, respectively. The rainfall during the crop growth period for the late sowing date preserves a slightly higher soil water content close to the soil surface, which helps to link the deeper soil moisture. However, in this instance, the crop had to use stored soil water due to insufficient rainfall through the early sowing date scenario, causing water stress and reduced grain yields and biomass. Under these drier conditions, root growth may be greater and is able to penetrate to the deeper layers, taking more subsoil water for the crop. As reported by Kirchhof et al. (2000a), under dry climate conditions, mungbean and peanut use higher subsoil water and root proliferation is deeper in order to satisfy water requirements for the crop growth.

The amount of water supply was most crucial for cowpea grain yield, which was sown at the early date (Figure 4). This indicates that the early sowing date led to a greater susceptibility of drought compared to the mid and late sowing dates. The low water supply during the early sowing date scenario creates dry soil conditions, causing poor germination and crop establishment, resulting in comparatively low grain yields (Rahmianna, 2007). Late sowing, therefore, ensures good establishment and growth, but it might be risky in practice, causing low soil water content for the following rice crop due to a narrow window between cowpea harvesting and rice sowing. Sowing time and soil water content at sowing for cowpea before rice cropping should be taken into account as highly important factors.

The model was also able to demonstrate the performance of cowpea after rice cropping at different sowing times and PAW levels. At the highest PAW, early sowing immediately after rice cropping in November resulted in high grain yields and biomass production with 40% of the spread being 438 and 1740 kg ha^{-1}, respectively (Figure 5a-b). Similar to the cowpea performance before rice cropping, at the low PAW, grain yields and biomass were low due to less water in the soil and a low water holding capacity. The amount of rainfall during the cowpea growing period after rice cropping was relatively low (Table 1 and 7), providing less water in the soil and influencing grain yields and biomass.

For the early sowing date, depending on the PAW, cowpea used 7-88 mm of water with mean grain yields ranging from 16 to 423 kg ha^{-1} and biomass ranging from 75 to 1722 kg ha^{-1}. For the mid and late sowing dates, the amount of water used was between 6 and 86 mm with mean grain yields and biomass ranging from 2 to 368 kg ha^{-1} and 10 to 1621 kg ha^{-1}, respectively (Table 8). The rainfall during the crop growth period for all sowing dates cannot maintain sufficient soil water levels close to the soil surface and were not able to meet crop water requirements. As a consequence, the crops used stored soil water for their growth. Cowpea sown immediately after rice, when the soil is still wet after the rainy season may ensure crop germination and emergence before the soil dries out. In this condition, the roots are able to proliferate since the soil is still wet, ensuring good crop establishment and growth. A delay in sowing at the end of December can reduce yields, because the puddled topsoil dries excessively and creates high soil strength that can inhibit root growth, causing poor establishment and growth (Kirchhof et al., 2000b).

A strong relationship between water supply and yield was indicated for cowpea sown after rice cropping (Figure 6). An increase in yield was related to an increased in water supply from sowing to maturity. After the harvesting of rice at the end of the rainy season, rainfall normally decreases. A good relationship between water supply and yield showed that yields were restricted by stored soil water during the period of growth. Studies on mungbean showed that good relationship between soil water storage and yield, strengthening the key role of soil water storage and its use by legumes in rice based cropping systems (Kirchhof et al., 2000a).

The performance of cowpea before and after rice cropping relies on the soil water content at sowing and the sowing date. For the cowpea before rice, when the sowing is done during the dry season, soil moisture availability is likely to be improved, as the rainfall is higher, particularly in the month before the rainy season. For the cowpea after rice, sowing the crop immediately after the rice harvest utilizes the good soil conditions that allow roots to penetrate and explore the subsoil water, reserving water for the crops under low rainfall conditions. The long period of rainfall in this site (6 months) may ensure a successful rice-cowpea rotation by providing sufficient water near the soil surface. Simulated grain yields were relatively low in comparison with the potential yield (1-2 ton ha^{-1}), but they were slightly higher compared to the yield from field experiments. In this experiment, cowpeas were sown after 6 months of a long duration rice cultivar and were not fertilized, depending mainly on rainfall availability. Under such limited inputs, yields tend to be low.

Specifying a suitable sowing period is challenging because the soil water content is influenced by rainfall and time of sowing. Rainfall probability before and after rice cropping, therefore, should be clearly assessed so that farmers are able to select suitable times for sowing and prevent excessively high soil strength. Simulation models are able to capture the complexity of the performance of cowpea in lowland rice-based cropping systems and can predict the yield and biomass of cowpea as well as soil water use related to climate variability. Further investigation is required to assess the intensification of the fallow phase on rainfed lowland rice with different cultivars or legumes species.

5. Conclusions

The APSIM model allows for the continuous simulation of soil, water and crops variables in lowland rice-based cropping systems with adequate accuracy to capture the effect of different rice-based cropping systems at a range of fertilizer rates and residue treatments. The prediction of rice phenology was accurate, as was the model's simulation of the effect of fertilizer rates on rice grain yields and biomass. However, the model was unable to capture the dynamic of cowpea grain yield. Sufficient and good quality experimental data sets would be required for further investigation of the model simulation.

The model also provides the continuous simulation of soil, water and crop variables in this system over a range of sowing dates and PAW levels for cowpea in the tropical climate of northeast Thailand. The long-term scenario analysis showed that sowing cowpea before or after rice cropping required a certain soil water content condition dependent of sowing time. Sowing cowpea in the dry season close to the onset of the rainy season will allow for reliable crop establishment and root growth as the soil surface is sufficiently moist. The supply of water from the remaining rainfall allows water through the deeper soil layers and contributes to grain and biomass production. Sowing cowpea in the dry season immediately after rice harvests provides suitable soil conditions to allow roots to penetrate and explore the subsoil water, contributing towards good crop establishment and growth. Successful cowpea production in lowland rice-based cropping systems should take rainfall, soil water at sowing and sowing date into account. The ability of the model to simulate such a system can provide useful information for farmers and be used to simulate the benefits and risks of using different legumes species.

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V. Intensifying the fallow phase of rice-based cropping systems for improving productivity across a range of agro-climatic environments in South Asia: A simulation study

1. Introduction

Rice is a staple food for most of the 1.7 billion people in South Asia and influences the livelihoods of more than 50 million people (IRRI, 2014). In 2013, nearly 60 million ha were harvested in this region and more than 225 million tons of paddy were produced. The cultivated rice area in South Asia is unlikely to expand but it may decrease because of the increased need for land for non-agricultural uses, whereas the South Asian population is projected to exceed 2 billion in 2030 (IRRI, 2014). In addition, water is becoming continuously scarce and the frequency of extreme weather events is continuing to rise which may reduce future rice productivity. Since the expansion of cultivated area is inaccessible, the increasing demand for rice productivity should be met by more intensive production systems.

In South Asia, rice-based cropping systems presented a considerable range of intensification levels with the majority of cropping systems growing one or two rice crops grown per year. Where the single rice crop system is the norm, this is generally done during the rainy season and is related to low risk and low input-output of the cropping systems (Davendra & Thomas, 2002). In areas with longer rainy season or additional irrigation, two rice crops are particularly grown per year. Another rice-based sequential cropping system such as rice-wheat, rice-rice-legumes and rice-maize is also practiced in this region (Dobermann, 2000). All systems have contributed to meet the need of food crops and have a considerable impact on farmers' income improvement.

Rice-wheat rotation is the predominant cropping system, covering around 30% of the rice and wheat area in South Asia (Ladha et al., 2003). In India, this system covers around 10 million ha and 85% of the total area is practiced in the India Indo-Gangetic plains (IGP) whereas in Pakistan, Bangladesh and Nepal covers around 2.2, 0.8 and 0.5 million ha, respectively (Ladha et al., 2000). Rice is typically grown during the rainy summer season (kharif season) from June to October, while wheat is grown during the dry winter season (rabi season) from November to March or April. The land, however, is usually left fallow between the wheat harvest and rice sowing.

Some farmers in the eastern part of IGP grow legumes, such as mungbean, soybean, chickpea or cowpea in rotation with rice and sometimes during the transition phase between wheat and rice cropping (Gupta et al., 2003).These crops are primarily used for food, fodder and green manure. The inclusion of legumes in the system provides a better nutritional balance and enhances soil and plant health as well as the productivity of the system (Singh & Ryan, 2015). In Bangladesh, a lot of farmers grow three rice crops in a year, the aus from April to July, aman from July to November, and boro rice crop from November to April (Gupta et al., 2003).

The main constraints of rice-based cropping systems in South Asia are climatic conditions and soil water status limiting timely crop establishment, and increasing cold stress pressure on the growing crop. In the area with sub-tropical to warm temperate, sub-humid, warm summer and mild cool winter climate conditions, rice usually has to deal with cold stress due to cool-temperatures at the latitude above 14°N. Crop establishment is consciously delayed, particularly at vegetative stage, to prevent cool-temperatures that may limit rice production (George et al., 1992).

Non-rice crops, such as wheat, legumes and maize are grown in the transition season, either before the onset of heavy rainfall or at the end of the rainy season (George et al., 1992; Singh et al., 2008; Balasubramanian et al., 2012). Wheat and winter legumes for instance, are typically grown during the cool season period. In Bangladesh, a selection of crops in this east region cautiously considers weather conditions because of the early rise of temperature and the long-higher average temperature, which may influence cool-season crops.

Rice establishment is commonly done by transplanting seedlings into the puddled soil and the field is continually flooded whereas non-rice crops are established into the tilled unflooded soils. Puddling for rice allows good crop establishment, improves nutrient availability, reduces deep percolation and eases weed control. However, it creates unfavorable effects on soil physical properties by destroying soil structure resulting in poor soil aeration and soil compaction, impairing the growth and yield of crops following paddy rice (Sharma et al., 2003; Gathala et al., 2011). The sub-soil water content is usually high for prolonged periods of inundation during the phase of rice in the rainy season, however, during the dry season root growth in the subsoil is often limited, causing roots are not able to use subsoil water reserves, and leading to poor germination and crop establishment. After the rice harvest, the puddled soil tends to dry quickly and it is difficult for roots to penetrate the zones of high soil strength, accordingly they may fail to reach subsoil water reserves (Kirchhof et al., 1996).

Another problem that can be found in most rice-wheat areas of South Asia is the late sowing of wheat (Fujisaka et al., 1994). Late sowing may cause poor germination and crop establishment, and consequently reduces yield. There are several causes for late sowing, namely the late harvest of the preceding rice crop or, in some cases, a third crop with short duration grown after rice (Hobbs & Gupta, 2003). The delayed onset of rainfall during the monsoon season in the eastern IGP also lead to late sowing as rice nursery and transplanting practices are delayed (Gupta et al., 2003). The other main cause of late sowing is the long turnaround time after the rice harvest, which is caused by some factors such as excessive tillage, soil moisture conditions, and how farmers managing the rice crop before land preparation for wheat (Hobbs & Gupta, 2003).

The optimum time period for sowing is likely narrow as a turnaround time of two weeks between rice harvest and sowing of the subsequent crop is normally considered as optimum (Kirchhof et al., 1996). During this time, soil can dry sufficiently and prevent extremely high soil strength. Also, the optimum soil water content for sowing is perceived to be crucial, and is determined by the rate of soil dries out and the rainfall after rice harvest. The time needed to meet a certain water content can be assessed if soil hydraulic properties, rainfall and evaporation are recognized. Sowing crop at the optimum soil water content does not guarantee that crop establishment will be successful. Therefore, climate conditions following sowing of the subsequent crop are important (Kirchhof et al., 1996).

Intensifying the rice-based cropping systems is challenging, as they are typically influenced by climatic conditions and soil water status, so that appropriate adapted rotation pattern and calendar is required to improve productivity and sustainability. Field trials have been conducted in South Asia to identify the proper sequences of crop and management practices (Gathala et al., 2013; Laik et al., 2014) in this system, but results obtained from such trials are limited for a short time period and are inadequate to capture spatial and temporal variability related to climate (Keating et al., 2002). Simulation models can provide insight into how the variability of rice-based system productivity across sites and years, and be used to identify high productivity options to reduce fallow. Besides, they allow evaluation of short and long-term management practices for agriculture with low cost and time requirements

(Malone et al., 2007). The Agricultural Production System Simulator (APSIM) model incorporates a range of agricultural variables to evaluate the impact of management practices (Keating et al., 2003; Holzworth et al., 2014). The APSIM model has been used to simulate reasonably the observed yields of many crops, such as rice, wheat, and legumes, and cropping systems (Probert et al., 1998a; Asseng et al., 2011; Gaydon et al., 2012; Mohanty et al., 2012; Amarasingha et al., 2015). However, information on the ability of the model to predict the performance of rice and non-rice crop cropping systems in diverse crop growing regions in South Asia is limited. To demonstrate the capability of the APSIM model, it is necessary that the model is tested in different cropping systems, management practices and locations. Therefore, the objective of this study is to: (i) calibrate and evaluate APSIM for simulating rice-based cropping systems considering alternative options to fallows with non-rice crops based on field experiment data from published sources from the IGP India, Tamil Nadu and Bangladesh (Gathala et al., 2013; Laik et al., 2014; Alam et al., 2015; Ladha et al., 2015); (ii) investigate productivity of intensification options using the long-term simulation of historical climate; (iii) identify potential rotations improving productivity of rice-based cropping system in South Asia.

2. Material and methods

The APSIM-ORYZA model was used to simulate 9 different rice-based cropping systems. The model has been well validated to simulate cereal based cropping systems in South Asia (Zhang et al., 2006; Gaydon et al., 2012; Mohanty et al., 2012) and for this work data from field experiments were used to calibrate and validate the model to simulate rice-based cropping systems across four sites of study representative of the main rice growing areas of the region. Simulations of scenarios were then carried out to assess different cropping rotations to define their productivity and their adaptability over the four sites.

2.1 Site description

The sites of study are four sites under diverse agro-climatic conditions in India and Bangladesh between 2009 and 2011 (Gathala et al., 2013; Laik et al., 2014; Alam et al., 2015; Ladha et al., 2015). The selected sites are Western IGP: Karnal, Haryana, India (29^o70’ N, 76^o96’ E); Central-IGP: Patna, Bihar, India (25^o24.912’ N, 85^o03.536’ E); Subtropical South India: Aduthurai, Tamil Nadu, India (11^o0.007’ N, 79°48' E); and Eastern-IGP: Gazipur, Bangladesh (23°59' N, 90°24.08' E).The climate ranged widely from semi-arid, hot sub-humid to sub-tropical. Based on daily weather records, annual average rainfall of Karnal, Aduthurai and Gazipur (1983-2013) is 773, 1087 and 2056 mm, respectively. For Patna (1982-2012), it is 1110 mm. Rainfall mainly occurs between June and September for Karnal and Patna, whereas between September to December for Aduthurai, and between May to September for Gazipur. The average daily minimum temperature of Karnal and Patna ranged from 6.5 to 26.2°C and from 9 to 26.5°C, respectively with the lowest values in January, while the average daily maximum temperature is varied in the range between 19.0 to 39.1°C and 21.6 to 37.4°C, respectively with the highest values in May. For Aduthurai and Gazipur, the average daily temperature is also lowest in January (20.5 to 26.1°C and 12 to 26.2°C, respectively) and highest from April to May (28.3 to 36.4°C and 24.8 to 33.6°C, respectively) (Figure 1).

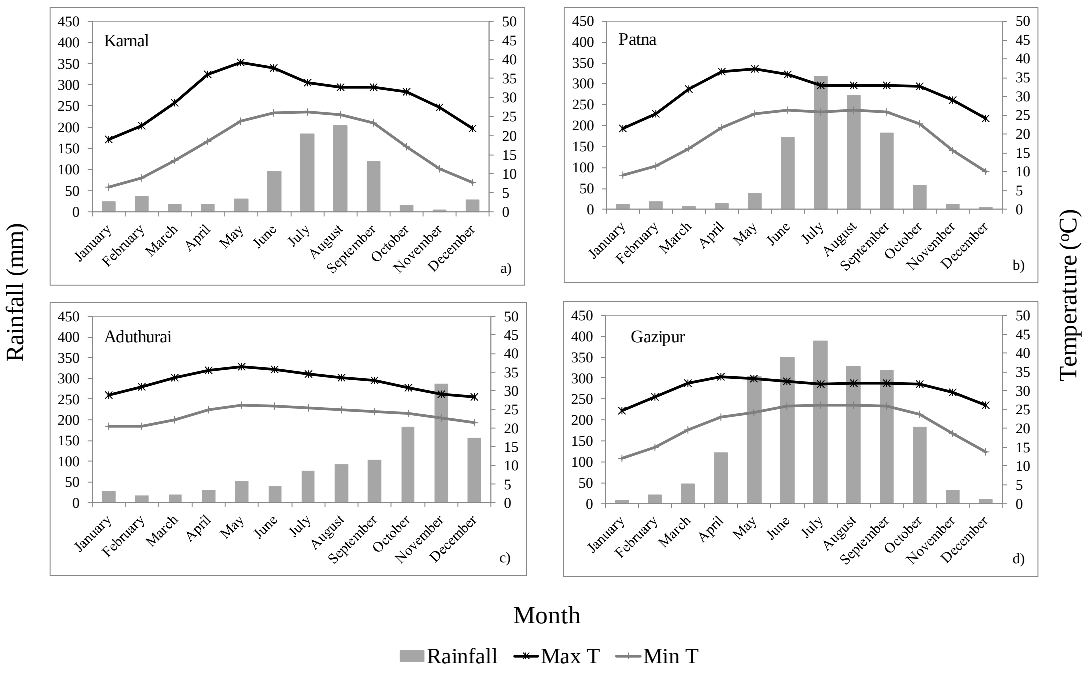


Figure 1: Average monthly rainfall, and monthly max (max T) and min (min T) daily temperature based on daily weather records of 30 years (from 1982/1983 to 2012/2013 for a) Karnal, b) Patna, c) Aduthurai and d) Gazipur in South Asia from the Indian and Bangladesh agricultural research weather stations.

2.2 Field description and design

The soils of four sites varied from loam, silty loam to clay with organic carbon content ranging from 0.56 to 1.20%. Each of the treatments was replicated thrice in a randomized complete block design.

a) Karnal

The soil was an alkali loam soil containing 34.03% sand, 46.07% silt and 19.89% clay with organic carbon content (OC; 0-15 cm) of 0.56% and pH (in water) 8. The field experiment was carried out from 2009 to 2011 at the Central Soil Salinity Research Institute (CSSRI) in Karnal, Haryana, India (Gathala et al., 2013). The treatments were laid out in a randomized complete block design consisting of rice and non-rice crops cropping systems by two rotations (rice-wheat-fallow and rice-wheat-mungbean), two establishment methods for rice (transplanted and direct seeded), and two crop residue treatments (crop residue removed and retained), with three replications. A summary of the systems and management practices is provided in Table 1.

b) Patna

The soil was non-calcareous non-saline old alluvium containing 16.8% sand, 41.8% silt and 41.4% clay with organic carbon content (OC; 0-15 cm) of 0.80% and pH (in water) 7.5. The field experiment was conducted from 2009 to 2011 at the Indian Council of Agricultural Research Complex for the Eastern Region (ICAR-RCER) in Patna, Bihar, India (Laik et al., 2014). The treatments were laid out in a randomized complete block design consisting of rice and non-rice crops cropping systems by three rotations (rice-wheat-fallow, rice-wheat-mungbean, and rice-wheat-cowpea), two establishment methods for rice (transplanted and direct seeded), and two crop residue treatments (crop residue removed and retained), with three replication (Table 1).

c) Aduthurai

The soil was clay soil containing 30.8% sand, 22.8% silt and 46.5% clay with organic carbon content (OC; 0-15 cm) of 1.20% and pH (in water) 7.5. The field experiment was conducted from 2009 to 2011 in Aduthurai, Tamil Nadu, India (Ladha et al., 2015). The treatments were laid out in a randomized complete block design consisting of rice and non-rice crops cropping systems by two rotations (rice-rice-blackgram, and rice-maize), two establishment methods for rice (transplanted and direct seeded), and two crop residue treatments (crop residue removed and retained), with three replication (Table 1).

d) Gazipur

The soil was clay soil containing 18% sand, 54% silt and 28% clay with organic carbon content (OC; 0-15 cm) of 1.10% and pH (in water) 4.8. The field experiment was carried out from 2009 to 2011 at the Bangladesh Agricultural Research Institute (BARI) in Gazipur, Bangladesh (Alam et al., 2015). The treatments were laid out in a randomized complete block design consisting of rice cropping systems by one rotation (rice-rice-fallow) and retained residue treatment with three replication (Table 1).

Field management: rotation and cropping seasons

For all sites, crop production was distributed across three seasons that occur in the considered area: the cool and dry winter season (rabi or boro; November to March), the hot and dry summer season (April to May), and the wet/rainy season (kharif or aman; June to November) except for Aduthurai where wet season starts from June to March. Before the start of the experiment, rice crop (cover crop) was grown across the sites to promote site uniformity. After harvest, the entire experimental area was leveled (zero gradient) using a laser-equipped drag scraper (TrimbleTM, Sunnyvale, CA, USA) with an automatic hydraulic system powered by a 60-HP tractor. The details of the field operations and crop management practices, including land preparation, variety, sowing or transplanting time, fertilizer application, water management, and pest management for the crops are described in Gathala et al.(2013); Laik et al. (2014);Alam et al. (2015); and Ladha et al. (2015).

Table 1: Crop sequences and management practices implemented for Karnal, Patna, Aduthurai and Gazipur.

Sites	Crop sequences (9)	Rice establishments	Residue treatments
Karnal	Rice-wheat-fallow	Transplanted	Removed
	Rice-wheat-mungbean	Transplanted	Retained full
	Rice-wheat-mungbean	Direct seeded	Retained full
Patna	Rice-wheat-fallow	Transplanted	Removed
	Rice-wheat-mungbean	Transplanted	Retained half
	Rice-wheat-cowpea	Direct seeded	Retained full
Aduthurai	Rice-rice-blackgram/mungbean	Transplanted	Removed
	Rice-rice-blackgram /mungbean	Transplanted	Retained fourth
	Rice-rice-blackgram/mungbean	Direct seeded	Removed
	Rice-maize	Direct seeded	Retained half
Gazipur	Rice-fallow-rice	Transplanted	Retained fourth

2.3 The APSIM model setup

The APSIM version 7.5 was configured with the modules for rice, wheat, mungbean, cowpea and maize, the soil water (SOILWAT), the soil N (SOILN), residue (Surface OM), and a crop Manager table (Keating et al., 2003). These modules were connected to the central engine of APSIM to simulate rice and/or non-rice crops within rice cropping system in South Asia. As the blackgram crop is assumed to present similar functioning as mungbean crop, mungbean module was used in the rice-blackgram simulations setup.

2.3.1 Soil setups

The SOILWAT and SOILN modules were parameterised following standard practices using APSIM. The input soil parameters were estimated from soil characterization data by Gathala et al.(2013); Laik et al. (2014); Alam et al. (2015); and Ladha et al. (2015) as previously described (Table 2). For all sites, the parameters for the SOILWAT module cover soil bulk density, saturated soil water content, drained upper limit water content at field capacity (DUL) and crop lower limit (Table 2).

The two parameters (U and CONA) that determine first and second stage of soil evaporation were set to 4 and 3 mm day^{-1} respectively. Runoff is linked to the setting of the USDA curve number and was set for all sites as 73. The fraction of water drained to the next soil layer under saturated conditions per day (SWCON) is 0.4 and 0.3 for all layers following standard parameterisation for a loam (Karnal and Patna) and clay soil (Aduthurai and Gazipur), respectively. For soil water content below

DUL, water movement relies on the gradient of water content between adjacent layers and the soil's diffusivity, defined in APSIM as diffusivity constant and diffusivity slope. The default values of 88 and 40 (diffusivity constant), and 35 and 16 (diffusivity slope) were used to reflect a loam and clay soil, respectively. The parameters for SOILN module include organic carbon (OC), pH, Finert (inert C fraction) and Fbiom (microbial biomass fraction) for all sites (Table 2). The OC content which was mainly measured for the top layer was presumed to decrease with depth. Finert and Fbiom, the different pools of the organic matter are based on typical default values representing the fraction of the total organic carbon in the specific pool (Probert et al., 1998b; Luo et al., 2014).

Recorded residue treatments from the field experiments were applied in the model setup (Table 1). The initial nitrogen content in the soil was set at 0-20 and 20-200 cm (NO_3: 6 and 4kg ha^{-1} (Karnal and Aduthurai), 10 and 8 kg ha^{-1} (Patna), 0.060 and 0.050 kg ha^{-1}(Gazipur); NH_4: 4 and 1kg ha^{-1}(Karnal and Aduthurai), 8 and 5 kg ha^{-1} (Patna), 0.040 and 0.010 kg ha^{-1} (Gazipur)). Initial water content at sowing was set to 100 % evenly distributed.

2.3.2 Plant module calibration and evaluation

The ORYZA2000 rice model (Bouman et al., 2001) was incorporated into the APSIM framework under the integrated name APSIM-ORYZA. APSIM-ORYZA has been validated in several studies (Zhang et al., 2006; Gaydon et al., 2012). In this study, APSIM-ORYZA was set to simulate the crop, soil and applied management during the field experiments of 2009-2010 across the four sites (Karnal, Patna, Aduthurai and Gazipur). In simulation of each system, rice crop varieties were calibrated by adjusting the ORYZA2000 parameters of crop phenology until the simulated phenology dates best fit with the observed dates. A similar process was complied with APSIM crops for wheat and maize. Phenological parameters were derived based on the recorded dates of sowing, transplanting and physiological maturity phase in the field experiments. Parameterisation of the mungbean and cowpea was limited by lack of experimental data in crop growth and development. Default values of crop parameters were then used for the mungbean (cv. Shantung) and the cowpea (cv. Banjo). After parameterization of the rice, wheat and maize crop phenology, model calibration was carried out in order to reach good agreement between simulated and observed values for grain energy yield (GEY) for cropping systems carried out in

2009-2010. The model ability to simulate various rice-based cropping systems across the four sites of study was then assessed and validated using the 2010-2011data from the same experimental sites.

2.4 Model performance analysis

Instead of grain yield, the grain energy yields (GEY) were used to represent system productivity. The GEY in GJ ha^{-1} is the energy obtained from the crop in harvested yield and was counted by multiplying the grain yield obtained in the field by crop grain energy conversion factor, on a dry weight basis (rice and wheat: 14.5 MJ kg^{-1}; maize: 14.31 MJ kg^{-1}; mungbean and cowpea: 14 MJ kg^{-1}) (Gopalan et al., 1978).

For statistical analysis of model calibration and evaluation, the observed GEY of system in the above-mentioned experiments were compared with the corresponding simulated values using linear regression. The comparison determined the slope (α), intercept (β) and coefficient of determination (R^2) of the linear regression. The root mean square error (RMSE) was predicted between observed and simulated paired-values to quantify the goodness of fit of these comparisons. The efficiency of forecasting (EF) was also used to evaluate the performance of the model (Loague and Green, 1991). The equation of RMSE and EF (Eq. (1) and Eq. (2)) as follows:

$$RMSE = [(\sum (O - P)^2/n)]^{0.5} \qquad (1)$$

$$EF = 1- [(\sum (O- P)^2) / (\sum (O - \bar{O})^2)] \qquad (2)$$

Where O and P are the paired observed and simulated values, $\bar{O}$ is the mean of all observed values and n is the total number of observations. The good model performance is indicated by lower values of RMSE (close to 0 and within the range of the standard deviation of the observed values), while the poor model performance is indicated by higher values of RMSE beyond the limit of the standard deviation of the observed values. The values of EF describe the overall goodness-of-fit of the data with values close to one indicating high performance of the model, and negative values indicating poor performance (Mayer and Butler, 1993).

Table 2: Soil Bulk density (BD), saturation (SAT), lower limit of plant-available water (LL15), drained upper limit of water (DUL), organic carbon (OC) for Karnal, Patna, Aduthurai and Gazipur at various soil depths for initiation of the APSIM model.

Site	Depth (cm)	BD (g cm^{-3})	SAT (mm mm^{-1})	DUL (mm mm^{-1})	LL15 (mm mm^{-1})	OC (%)	Fbiom	Finert
Karnal	0-15	1.20	0.48	0.27	0.12	0.56	0.07	0.20
	15-30	1.20	0.48	0.27	0.12	0.34	0.05	0.40
	30-60	1.21	0.47	0.26	0.13	0.34	0.03	0.55
	60-90	1.22	0.46	0.26	0.14	0.27	0.02	0.85
	90-120	1.23	0.45	0.25	0.14	0.27	0.02	0.95
	120-150	1.23	0.43	0.24	0.14	0.27	0.01	0.95
Patna	0-15	1.30	0.51	0.40	0.25	0.80	0.04	0.40
	15-30	1.30	0.51	0.40	0.25	0.57	0.02	0.60
	30-60	1.20	0.50	0.39	0.26	0.44	0.02	0.80
	60-90	1.18	0.49	0.38	0.27	0.37	0.02	0.90
	90-120	1.15	0.49	0.38	0.27	0.37	0.01	1.00
	120-150	1.15	0.49	0.38	0.27	0.37	0.01	1.00
Aduthurai	0-15	1.40	0.40	0.28	0.14	1.21	0.03	0.40
	15-30	1.40	0.40	0.28	0.14	0.93	0.03	0.40
	30-60	1.40	0.40	0.27	0.15	0.83	0.02	0.50
	60-90	1.41	0.39	0.24	0.16	0.62	0.02	0.60
	90-120	1.42	0.38	0.24	0.17	0.55	0.01	0.80
	120-150	1.42	0.38	0.24	0.17	0.51	0.01	0.80
Gazipur	0-15	1.35	0.49	0.35	0.18	1.09	0.04	0.40
	15-30	1.35	0.49	0.35	0.18	0.71	0.02	0.60
	30-60	1.36	0.47	0.34	0.19	0.58	0.02	0.80
	60-90	1.37	0.46	0.33	0.20	0.38	0.02	0.90
	90-120	1.37	0.45	0.33	0.20	0.23	0.01	1.00
	120-150	1.37	0.45	0.33	0.20	0.15	0.01	1.00

2.5 Scenario analysis

Crop model simulations were developed to evaluate variability of rice-based system productivity among sites and years, and to identify high productivity options to reduce fallow. These systems were examined for Karnal, Patna, Aduthurai and Gazipur site using climate data from 1982 to 2013. 20 combinations of crop sequence-rice establishment-residue treatment were setup to represent range of cropping systems with variability of productivity as described as follows:

(i) Crop sequence: rice-wheat-fallow, rice-wheat-mungbean, rice-wheat-cowpea, rice-maize, and rice-fallow-rice.

(ii) Rice establishment method: rice was set transplanted and direct-seeded for each crop sequence.

(iii) Residue treatment: crop residues were set retained and removed for each crop sequence. For the residue retained treatment, an amount of residue ranging from 2 to 8 ton ha^{-1} was retained in the field after harvest.

(iv) Planting time for rice: early and late sowing of the first rice crop was considered corresponding to crop sown in June and in July during the wet/rainy season (kharif) respectively.

(v) Planting time for the second main crop (wheat, maize and rabi rice): early and late sowing corresponded to crop sown in November-December during the dry winter season (rabi) respectively.

(vi) Planting time for the inter-season crop (mungbean and cowpea): mungbean and cowpea as the third crop was sown in April during the hot, dry summer season.

The soil parameterisation was set similar to the calibration and evaluation runs and representative for each soil type in the study sites (Table 2). Fertilizer and irrigation application as well as crop varieties used were also set similar to the evaluation runs for each system. All systems above were arranged using the language of APSIM's Manager and the SoilWat module. For Karnal, Aduthurai and Gazipur, simulations began on the 1st of November 1983 and ran until the 31st of December 2013. For Patna, simulations began on the 1st of November 1982 and ran until the 31st of December 2012. Soil water, soil mineral N and soil organic matter were reset to initial conditions before the start of each year.

For data analyses, cumulative distribution functions were used to calculate the probability of system productivity (GEY) of diverse crop sequence-rice establishment-residue treatments for each study site. The GEY of a system in a year was computed as the total GEY for each crop in the system, and averaged it over years for a rotation afterwards. A high productive system was defined as a system with the high GEY over the years.

3. Results

3.1 Calibration of the APSIM-ORYZA model

APSIM-ORYZA has presented high accuracy in simulating rice-based cropping systems productivity using the grain energy yield as indicators. Good agreement was obtained during the crop calibration between simulated and observed values for GEY for cropping systems carried out in 2009-2010 with R^2: 0.71, RMSE: 24.63 (Figure 2) and EF: 0.84 (Table 3).

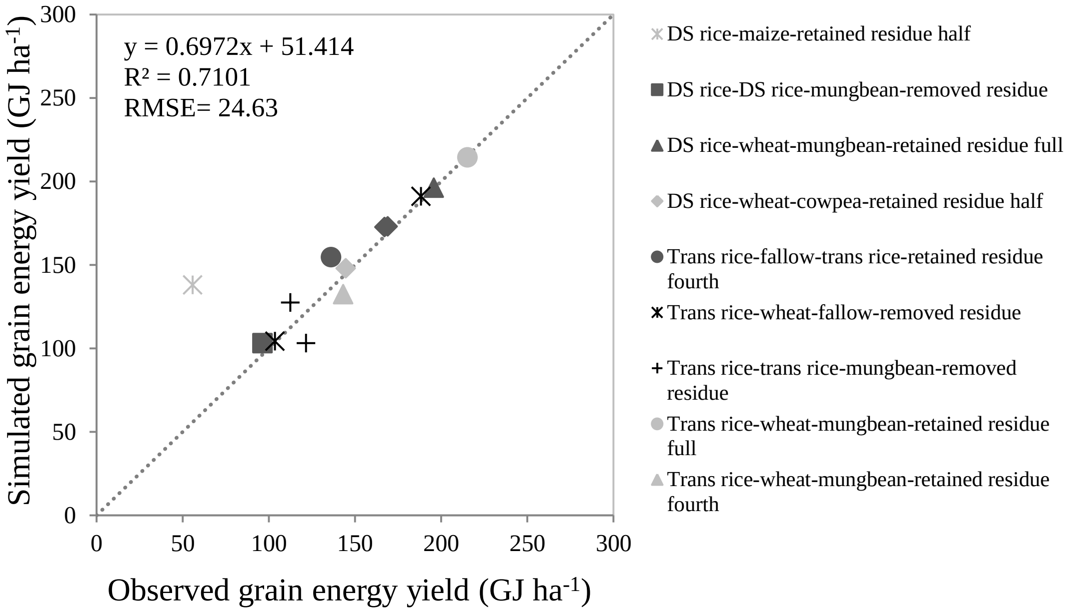


Figure 2: Observed versus simulated grain energy yield (GEY) in GJ ha^{-1}across study sites and combinations of crop sequence, rice establishment and residue treatment from 2009-2010 (DS: direct-seeded; Trans: Transplanted). The dotted line represents the 1:1 line.

3.2 Evaluation of the APSIM model

The model was evaluated for its performance in simulating 9 diverse crop sequences of the 2010-2011 experiments. These experiments were used to test the effect of different rice establishments and residue treatments at a range of agro-climatic conditions in IGP India, Tamil Nadu and Bangladesh. Figure 3 shows scatter plots (1:1) of simulated GEY against observed data for cropping systems identified individually as a combination of crop sequence, rice establishment and residue treatment. Data from field experiments comprised of a range in GEY (68-198 GJ year^{-1} ha^{-1}) for the 2010-2011 year round with an average of GEY of 147 GJ ha^{-1}. Both the transplanted rice-wheat-mungbean and the direct-seeded rice-wheat-mungbean rotations with retained residue treatment presented higher GEY than other cropping systems, whilst the transplanted rice-wheat-cowpea rotation with retained residue treatment showed the lowest GEY.

Simulated GEY presented a good fitness with the observed data with a RMSE of 12.29 GJ ha^{-1}. The RMSEn (normalized root mean square error) (%) was of 8 corresponding to a model efficiency (EF) of 0.94 (Table 3). The value of RMSE and RMSEn in validation was much lower than in calibration, whereas the value of R^2 and EF was higher in validation than in calibration. This indicates that the model has been well calibrated using our procedure of calibration although the lack of data and it was able to capture the variability within the years as the validation has presented also a good accuracy referring to RMSE, RMSEn and EF.

During the validation, there was an outlier for GEY of transplanted rice-transplanted rice-mungbean rotation with retained residue treatment. This value was not in the pattern of values produced by the rest of the data. The GEY of the first rice crop was doubled than the rest of GEY values of the same crop. This outlier was then excluded from the evaluation of the model.

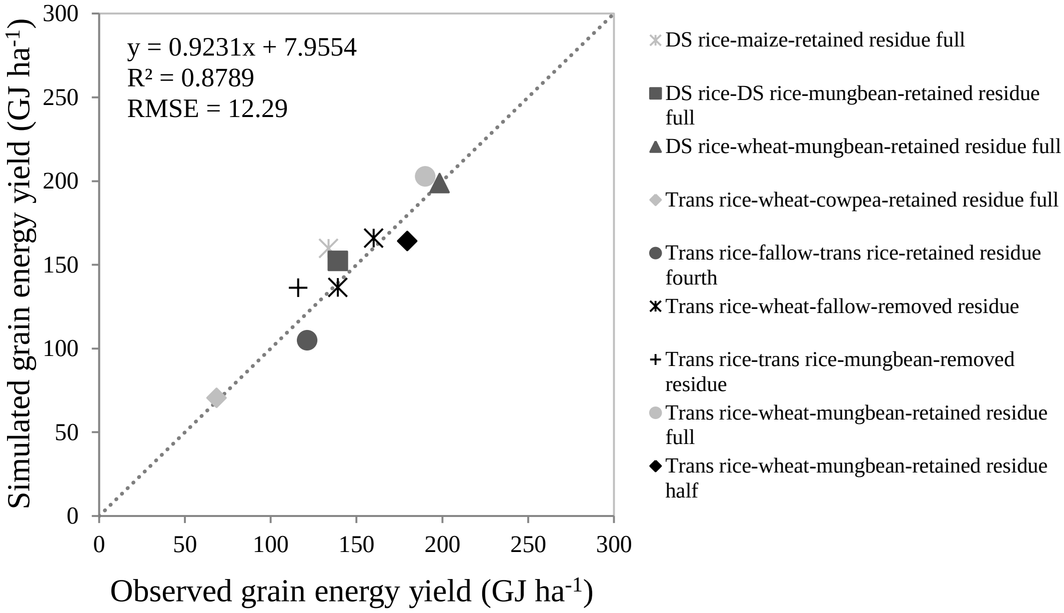


Figure 3: Observed versus simulated grain energy yield (GEY) in GJ ha^{-1} across study sites and combinations of crop sequence, rice establishment and residue treatment from 2010-2011 (DS: direct-seeded; Trans: Transplanted). The dotted line represents the 1:1 line.

Table 3: Statistical criteria (root mean square error, RMSE and model efficiency, EF) as well as observed range and mean for evaluating grain energy yield (GEY) of system for the model calibration and validation.

Parameters	N	Observed range (GJ ha^{-1})	Observed mean (GJ ha^{-1})	RMSE	RMSEn (%)	EF
GEY of systems for calibration (2009-2010)	13	56-215	142	24.63	17	0.84
GEY of systems for validation (2010-2011)	12	68-198	147	12.29	8	0.94

3.3 Scenario analysis

Variability of different rice-based cropping systems productivity was assessed across the four study sites through scenarios analysis. Simulated GEY did not present significant differences between the removed and retained residue treatments (*p*: 0.32). As simulated GEY of systems do not show differences between the removed and retained residue treatments, the value of retained residue treatment is given. The rice-fallow-rice system was set as a reference system for all sites.

a) Karnal

Figure 3a-b presents the variability of system productivity for transplanted and direct-seeded rice in Karnal. The crop sequence of rice-wheat-mungbean and rice-fallow-rice has presented the maximum and minimum GEY simulated respectively in this site. Among systems with transplanted rice, 50% of the seasons of the rice-wheat-mungbean system resulted in GEY >209 GJ ha^{-1}, whereas for the rice-fallow-rice system 60% of the spread of GEY were <16 GJ ha^{-1}. Among systems with direct-seeded rice, similar distribution was observed with 50% of the seasons of the rice-wheat-mungbean system resulting in GEY >219 GJ ha^{-1}. For the rice-fallow-rice system, 60% of the spread of GEY were <22 GJ ha^{-1}. The rice-wheat-mungbean system would achieve higher GEY than the reference around 165 and 191 GJ ha^{-1} with the transplanted and direct-seeded rice respectively, 80% of the seasons.

The rice-wheat-cowpea system with transplanted rice and the rice-wheat-fallow with direct-seeded rice tended to be the stabile systems as they had narrower distribution of GEY than the other systems, showing less variation in GEY. The rice-fallow-rice system was the riskiest system due to its highest probability resulted in low GEY.

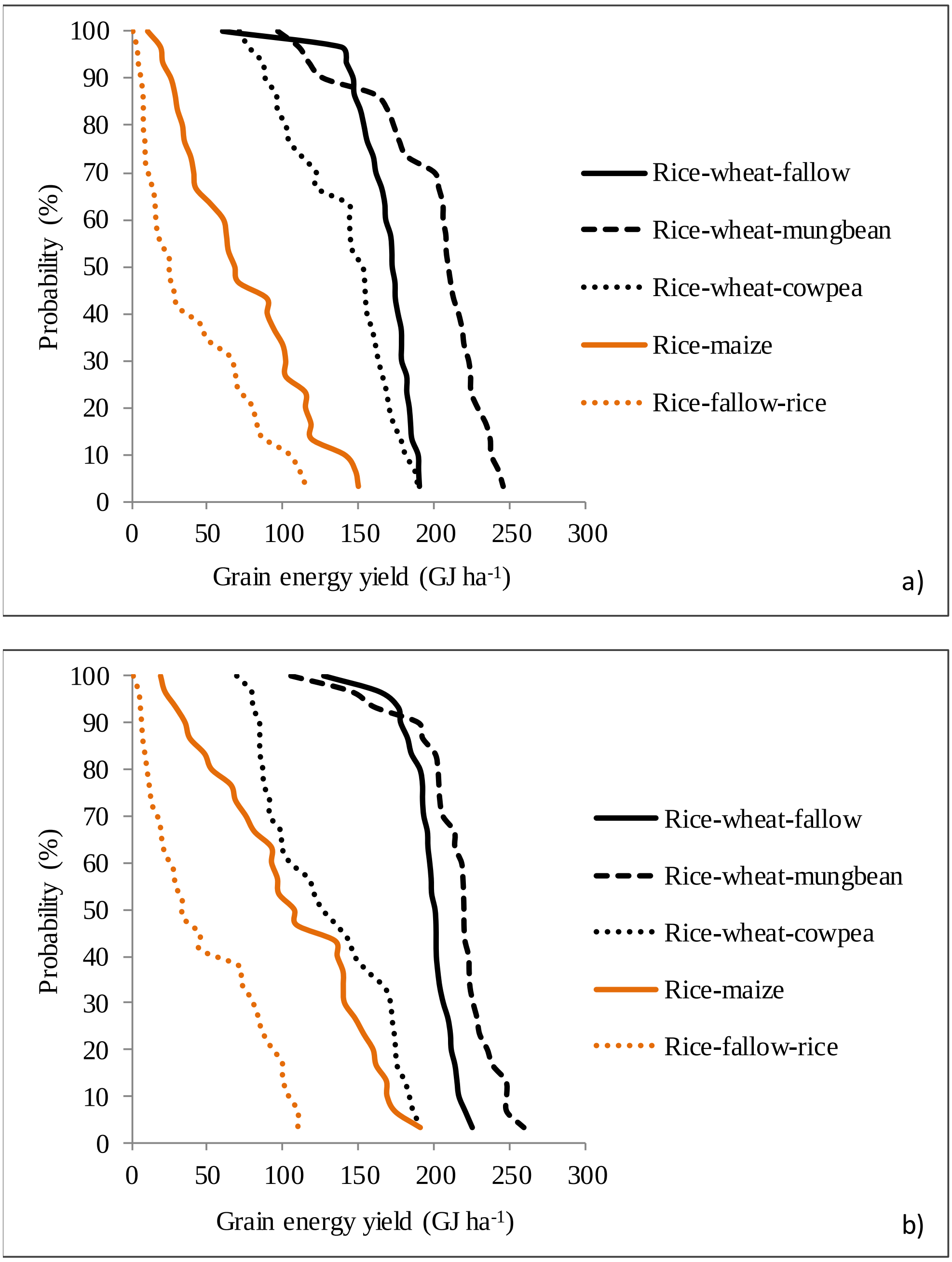


Figure 3a-b: Exceedance probability for APSIM simulations of grain energy yield of diverse crop sequences (GJ ha^{-1}) with a) transplanted and b) direct-seeded rice across the 1983-2013 climate records for Karnal site.

b) Patna

The variability of system productivity for transplanted and direct-seeded rice in Patna is presented in Figure 4a-b. The crop sequence of rice-wheat-mungbean and rice-fallow-rice has presented the maximum and minimum GEY simulated respectively.

Among systems with transplanted rice, 50% of the seasons of the rice-wheat-mungbean system resulted in GEY >189 GJ ha^{-1}, whereas for the rice-fallow-rice system 60% of the spread of GEY were <35 GJ ha^{-1}. Among systems with direct-seeded rice, similar distribution was observed with 50% of the seasons of the rice-wheat-mungbean system resulting in GEY >183 GJ ha^{-1}. For the rice-fallow-rice system, 60% of the spread of GEY were <43 GJ ha^{-1}. The rice-wheat-mungbean system would achieve higher GEY than the reference around 114 and 125 GJ ha^{-1} with the transplanted and direct-seeded rice respectively, 80% of the seasons.

The rice-wheat-fallow system with both transplanted and direct-seeded rice was the stabile systems as it showed the narrowest distribution of GEY, indicating less variation in GEY. The rice-fallow-rice system was the riskiest system due to its highest probability resulted in low GEY.

c) Aduthurai

The variability of system productivity for transplanted and direct-seeded rice in Aduthurai is given in Figure 5a-b. The crop sequence of rice-wheat-mungbean and rice-wheat-cowpea has presented the maximum and minimum GEY simulated respectively in this site. Among systems with transplanted rice, 50% of the seasons of the rice-wheat-mungbean system resulted in GEY >185 GJ ha^{-1}, whereas for the rice-wheat-cowpea system 80% of the spread of GEY were <74 GJ ha^{-1}. Among systems with direct-seeded rice, similar distribution was observed with 50% of the seasons of the rice-wheat-mungbean system resulting in GEY >180 GJ ha^{-1}. For the rice-wheat-cowpea system, 80% of the spread of GEY were <64 GJ ha^{-1}. The rice-wheat-mungbean system would achieve higher GEY than the reference around 72 and 6 GJ ha^{-1} with the transplanted and direct-seeded rice respectively, 80% of the seasons.

The rice-wheat-mungbean system with both transplanted and direct-seeded rice was the most stable system as it showed the narrowest distribution of GEY, indicating less variation in GEY. The rice-wheat-cowpea and the rice-maize system tended to be the riskier systems as they showed higher probability resulted in low GEY compared to the reference system.

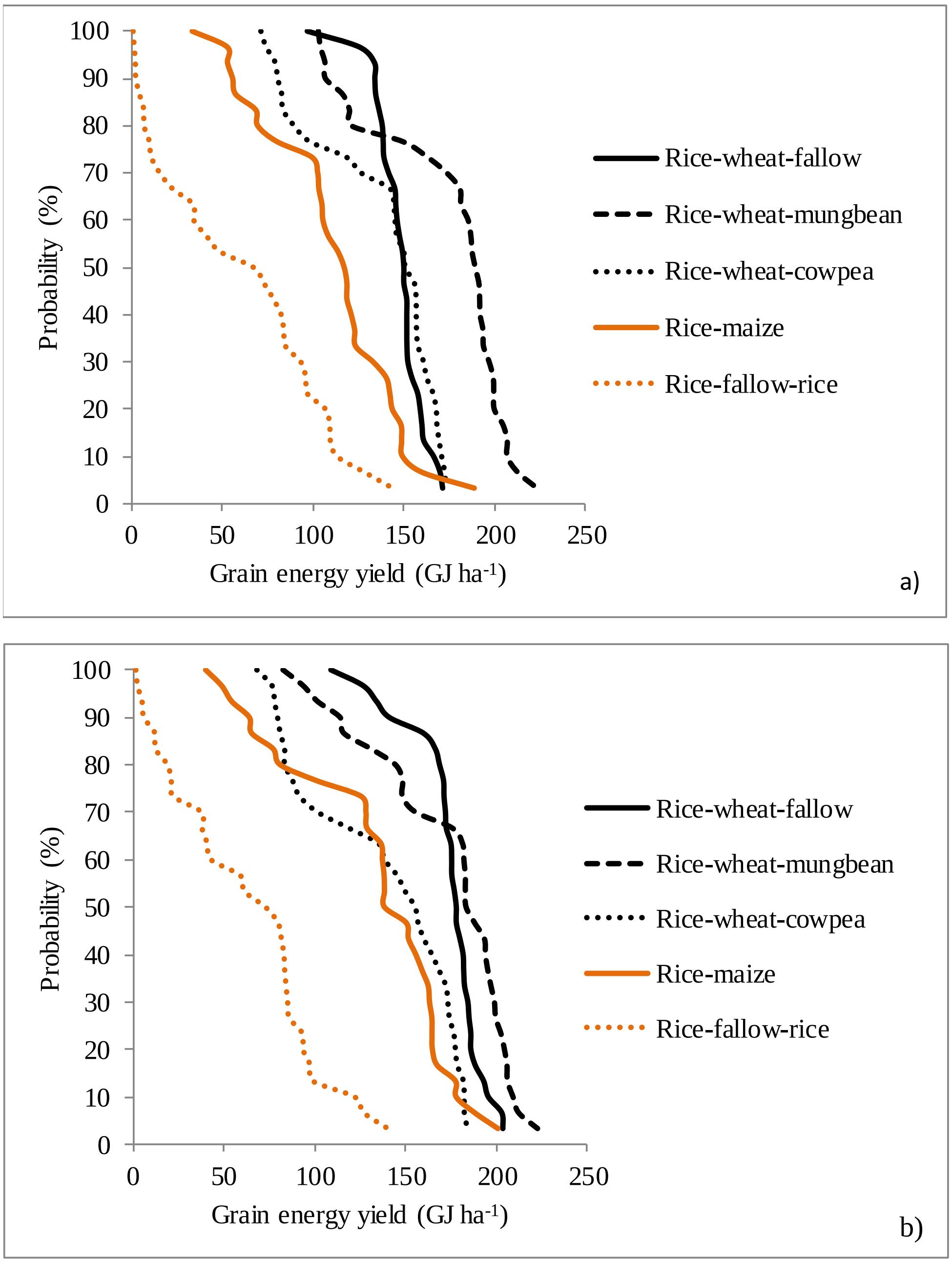
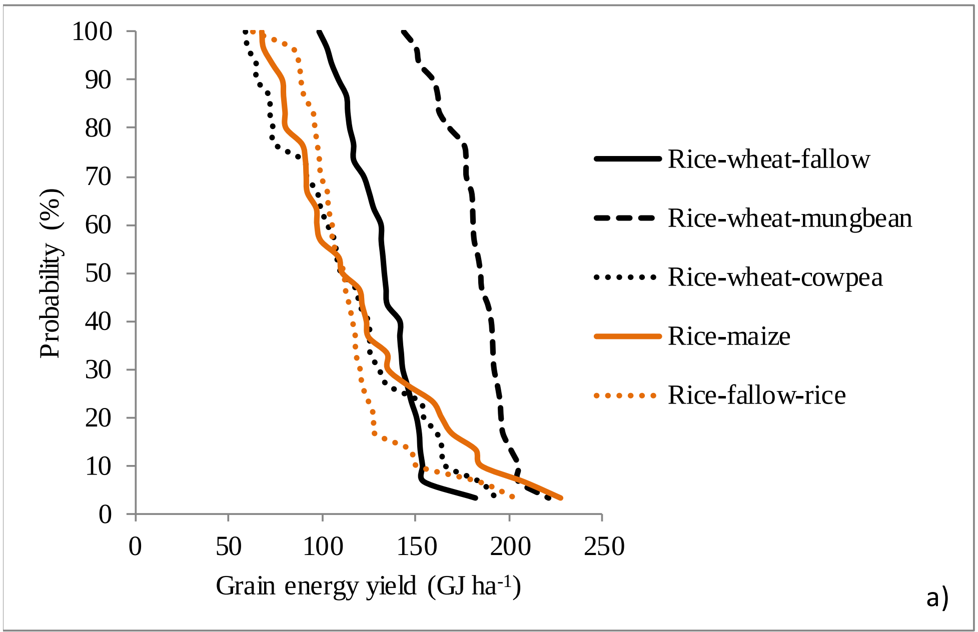


Figure 4a-b: Exceedance probability for APSIM simulations of grain energy yield of diverse crop sequences (GJ ha^{-1}) with a) transplanted and b) direct-seeded rice across the 1982-2012 climate records for Patna site.



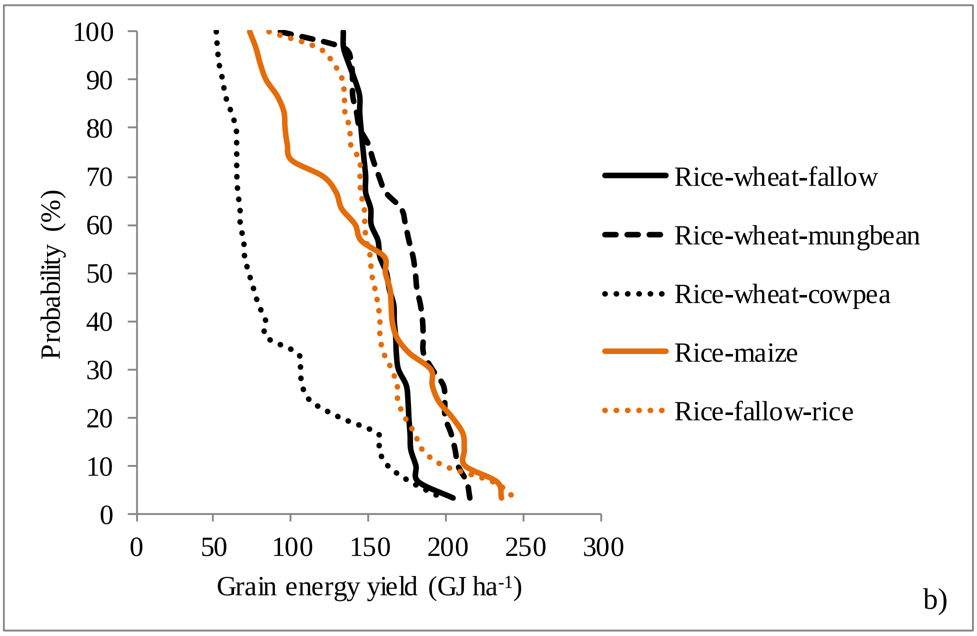


Figure 5a-b: Exceedance probability for APSIM simulations of grain energy yield of diverse crop sequences (GJ ha^{-1}) with a) transplanted and b) direct-seeded rice across the 1983-2013 climate records for Aduthurai site.

d) Gazipur

Figure 6a-b presents the variability of system productivity for transplanted and direct-seeded rice in Gazipur. The crop sequence of rice-fallow-rice and rice-maize has presented the maximum and minimum GEY simulated respectively. Among systems with transplanted rice, 50% of the seasons of the rice-fallow-rice system resulted in

GEY >180 GJ ha^{-1}, whereas for the rice-maize system 80% of the spread of GEY were <89 GJ ha^{-1}. Among systems with direct-seeded rice, similar distribution was observed with 50% of the seasons of the rice-fallow-rice system resulting in GEY >179 GJ ha^{-1}. For the rice-maize system, 80% of the spread of GEY were <94 GJ ha^{-1}. The rice-wheat-mungbean system with both transplanted and direct-seeded rice was the stabile system as it showed the narrowest distribution of GEY, showing less variation in GEY. The rice-maize system was the riskiest system due to its highest probability resulted in low GEY.

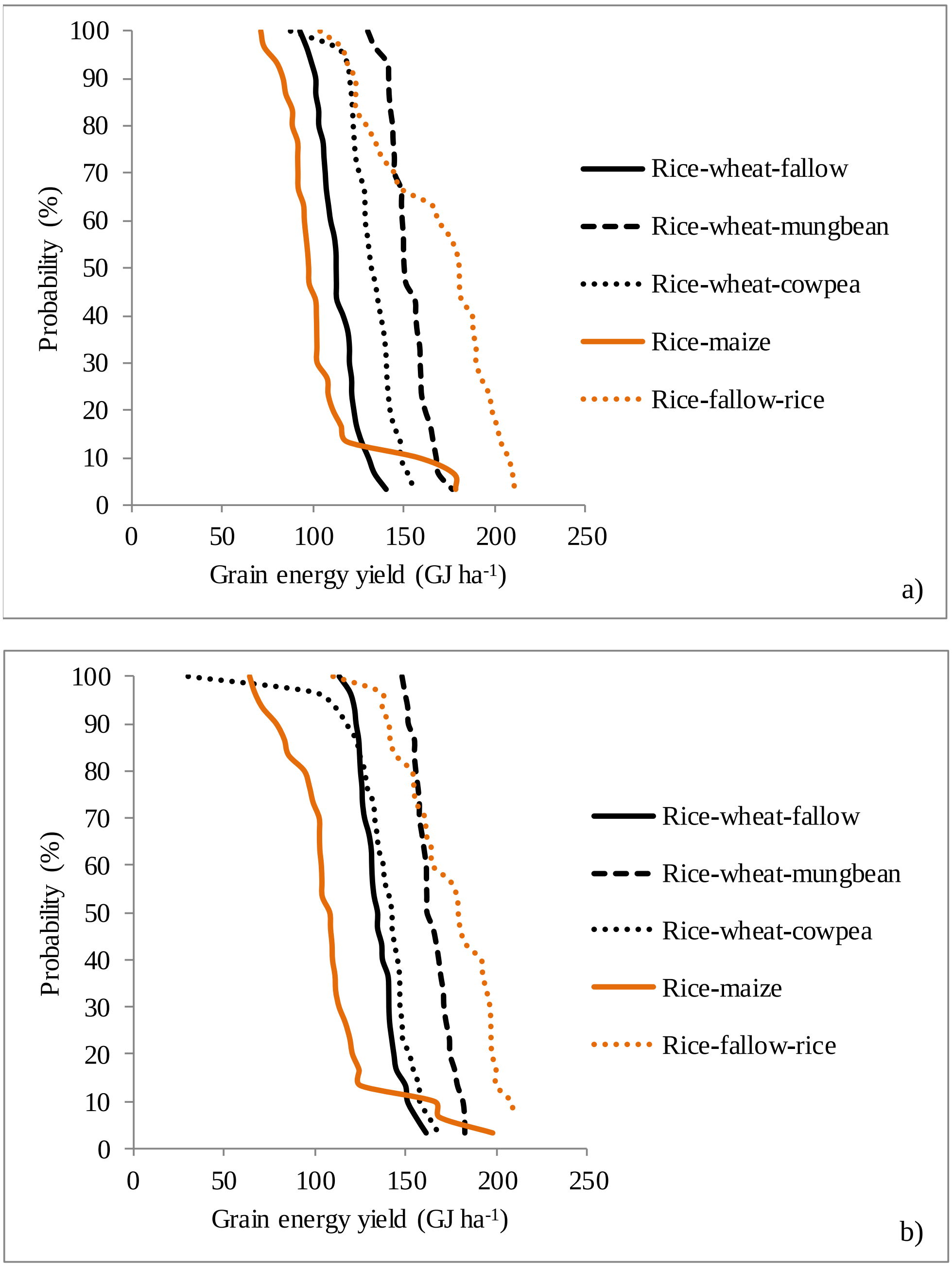


Figure 6a-b: Exceedance probability for APSIM simulations of grain energy yield of diverse crop sequences (GJ ha^{-1}) with a) transplanted and b) direct-seeded rice across the 1983-2013 climate records for Gazipur site.

Comparing the site productivity, Aduthurai and Gazipur tended to be more productive compared to Patna and Karnal (Table 4). In Aduthurai, each system performed relatively high GEY, whereas in Karnal and Patna, the rice-fallow-rice and the rice-maize system resulted in low GEY. The rice-wheat-mungbean system showed high GEY in all sites. Simulated GEY was highest in Karnal (197-212 GJ ha^{-1}) and lowest in Gazipur (152-165 GJ ha^{-1}), depending on rice establishment. Differences were in the range of 45-47 GJ ha^{-1}. For the low system productivity, the rice-fallow-rice system was the lowest in Karnal (39-47 GJ ha^{-1}) and Patna (57-60 GJ ha^{-1}). At Aduthurai, the lowest system productivity was the rice-wheat-cowpea system (91-113 GJ ha^{-1}), whereas at Gazipur was the rice-maize system (103-109 GJ ha^{-1}). The GEY of systems with direct-seeded rice were mostly higher than the transplanted rice.

Table 4: Simulated average grain energy yield (GEY in GJ ha^{-1}) of diverse crop sequences with transplanted and direct-seeded rice across 30 years climate records for Karnal, Patna, Aduthurai and Gazipur. Mean (n=30) and standard deviation (in brackets) are presented.

Rice establishments	Crop sequences	GEY (GJ ha^{-1}) at sites			
		Karnal	Patna	Aduthurai	Gazipur
Transplanted	Rice-wheat-fallow	166 (25)	147 (15)	132 (19)	113 (11)
	Rice-wheat-mungbean	197 (40)	173 (37)	182 (18)	152 (11)
	Rice-wheat-cowpea	139 (35)	136 (35)	113 (38)	132 (14)
	Rice-maize	73 (41)	110 (37)	120 (43)	103 (26)
	Rice-fallow-rice	39 (36)	57 (45)	114 (28)	167 (33)
Direct-seeded	Rice-wheat-fallow	196 (19)	173 (21)	156 (31)	135 (11)
	Rice-wheat-mungbean	212 (31)	172 (39)	173 (29)	165 (10)
	Rice-wheat-cowpea	129 (41)	137 (42)	91 (41)	136 (25)
	Rice-maize	105 (51)	132 (45)	150 (50)	109 (28)
	Rice-fallow-rice	47 (38)	60 (40)	156 (31)	174 (26)

4. Discussions

4.1 Model performance

The performance of cropping systems across all study sites had been calibrated and assessed using data from the field experiment conducted on research institutes in IGP India, Tamil Nadu and Bangladesh between 2009 and 2011 (Gathala et al., 2013; Laik et al., 2014; Alam et al., 2015; Ladha et al., 2015). The results of this study showed that the calibrated APSIM-ORYZA model sufficiently simulated the GEY of rice-based cropping system for diverse treatments, as evaluated through comparison of observed and simulated values and goodness of fit parameters (Figure 2). The model is able to demonstrate 71% of the variation in GEY imposed by crop sequence, rice crop establishment method and residue treatment applications, indicating that it captured much of the observed variation.

For the model evaluation, the simulation of GEY captured a variation of 88% (Figure

3) and a RMSEn prediction of 8% (Table 3), which is acceptable in crop model simulations (Jamieson et al., 1991). This indicates the sufficiency of the model to simulate GEY in response to different rice-based cropping systems and sites with soil and climate variations. In this study, the successful simulation of rice-based cropping systems (including crop sequences, rice establishments, residue treatments, crop varieties, season types and another management practices) allows much higher accuracy confirming the model ability to capture rationally main system processes in the crop and soil. Studies have reported that in simulating the performance of a single crop, crop model may confirm the whole of system process as the input parameters of the models are primarily adjusted (Bellocchi et al., 2010). In addition, specific crop model such the original stand-alone ORYZA2000 model was able to simulate the performance of rice at a range of management practices (Boling et al., 2004; Bouman and van Laar, 2006), but it could not simulate crop sequence that may include rice under any cropping system.

The focus of the testing was rice-based cropping systems which represent crop sequences considering alternative options including non-rice crops. The APSIM-ORYZA model has demonstrated its strength in simulating the performance of rice and non-rice crops in rotation and the performance of transplanted and direct-seeded rice on varied soil types and environments. The model was also able to simulate the impact of residue treatments on the GEY of system. Similarly, another study was carried out by Gaydon et al. (2012) shows the robustness of the model in simulating rice-based cropping system at varied geographical locations, soil types, crop sequences and agronomic practices such as crop establishment, irrigation and fertilizer application. However, they identified that the simulation of residue retained treatment has a tendency to underestimate the grain yields due to the model over predicting N immobilization during residue decomposition.

For the long-term scenario analysis, simulations were performed over 30 years, simulating continuous dynamics of crops, soil and water (Figure 3, 4, 5 and 6). The APSIM-ORYZA model was able to capture the advantages of the intensification options moving from fallow to other non-rice crops, and the difference of performance of transplanted and direct-seeded rice over a large time scale. The impact of residue retained on the GEY of system, however, did not have that much difference compared to the residue removed treatment. Also, when the simulations were run without any soil variable resets, allowing considering effect of continuous residue decomposition. The GEY of system in the residue retained were similar to the residue removed treatment (data not shown). This may indicate insufficiency in calibration of the model to due to lack of data describing soil processes related to the variability of indigenous soil nitrogen supply and its interaction with fertilizer and residue management. Our setting was unlikely to capture the effect of residue retention. However, other simulation studies on sugar cane residues also showed similar results (Thorburn et al., 2001). At 100 days of incubation, the simulated residue mass of sugar cane was lower compared to the observed ones as the initial mass of residue applied in the experiment was less than 5-7 ton ha-^{1}. The low initial mass of residue may delay the rate of residue decomposition. In this experiment, the amount of residue applied to the crops was normally less than 8 ton ha^{-1} and some wheat crops received 9-10 ton ha^{-1} of rice residues. The small amount of residues and low C:N ratio, particularly for the legumes caused a slow rate of decomposition and hence the N mineralization was likely delayed. In addition, the impact of the residues quality on decomposition may not be sufficiently described by the C:N ratio factor, which is crop-specific in the APSIM model (Probert et al., 1998b, Thorburn et al., 2001). Further testing of the model in the simulation of cropping systems with detailed residues data sets would be useful in improving the model performance in such systems and to consider long-term responses.

4.2 Scenario analysis

Scenario analysis demonstrates the capability of the model to examine productivity of intensification options and to explore potential rotations improving productivity of rice and non- rice crops within rice-based cropping system across the four study sites.

a) Karnal

The rice-wheat-mungbean system showed the highest performance with 80% of the seasons resulting in GEY >173 and >202 GJ ha^{-1} with transplanted and direct-seeded rice respectively in Karnal (Figure 3a-b). The rice-fallow-rice system showed the lowest performance with 80% of the seasons resulting in GEY <8 and <11 GJ ha^{-1} with transplanted and direct-seeded rice respectively. Comparing to the rice-fallow-rice (reference) system, Karnal would achieve higher GEY around 165-191 GJ ha^{-1} 80% of the seasons dependent of rice establishment by practicing the rice-wheat-mungbean system.

The rice and wheat crop is primarily cultivated in this area, following the climatic conditions. Rice crop is generally grown during the warm, sub-humid rainy season (June-October), whereas wheat crop is grown during the cool and dry winter season (November-March) (Gupta et al., 2004). The selection of rice and wheat as the rainy season and the dry winter season crop respectively was suitable in this site and hence optimizing yield. Besides, both crops were sown at the early time, allowing optimum conditions for good crop establishment and growth. The inclusion of mungbean in the rice-wheat-mungbean system also provides additional GEY of the system (~12% higher than the rice-wheat-fallow system), resulting higher productivity. The mungbean crop is able to fix N in the soil and requires less water to obtain a good yield (Chadha, 2010). On the other hand, the low productivity of rice-fallow-rice system compared to the rice-wheat-mungbean system was likely due to seasonal effects (rainfall and average daily minimum temperature), particularly for the second/rabi rice crops. The rainfall and average daily minimum temperature during the growing season of the second/rabi rice crop (November-April) was lower than the first/kharif rice crop (June-November) (Figure 1a). The yield tended to be lower in the second rice than in wheat crop. The second rice crop was mostly not able to grow due to the cold temperature, resulting complete crop failure and hence low GEY of the system. The low temperature may delay germination, and in several Asian rice cultivar, the temperature below 10^{o}C resulted germination failure (Lee, 2001). A study in growth-chamber indicated that germination was decreased by 10–22% when temperature was decreased from 21 to 11^{o}C (Ali et al., 2006). In this experiment, the average daily minimum temperature during the second rice crop growing season was around 7^{o}C, causing the germination failure.

The rice-wheat-cowpea system with transplanted rice and the rice-wheat-fallow with direct-seeded rice showed the narrowest distribution of GEY, indicating less variation in GEY and hence were considered as the stabile systems. These systems provide greater stability of GEY than the other systems and increase resilience to various environmental constraints. The rice-fallow-rice system was not only the lowest system productivity but also a riskiest system. The selection of rice crop as the second crop during the dry winter season was not appropriate as rice crop requires warm temperature for its growth, particularly during emergence and crop establishment (George et al., 1992). Consequently, the second rice crop establishment was limited, resulting crop failure and hence reducing GEY of the whole system.

b) Patna

Similar to Karnal site, the productivity of the rice-wheat-mungbean system was the highest in Patna, but magnitudes differed to a large extend. In this system, 80% of the seasons resulted in GEY >121 and >144 GJ ha^{-1} with transplanted and direct-seeded rice respectively (Figure 4a-b). The productivity of the rice-fallow-rice system was the lowest with 80% of the seasons resulting in GEY <7 and <19 GJ ha^{-1} with transplanted and direct-seeded rice respectively. Comparing to the reference system, Patna would achieve higher GEY around 114-125 GJ ha^{-1} 80% of the seasons dependent of rice establishment by practicing the rice-wheat-mungbean system. By selecting the right crop for the given soil and climate conditions, and sowing crop in the proper time would provide optimum condition for crop establishment and growth, so that optimizing yield. In this site, sowing rice and wheat during the rainy and dry winter season respectively at the early sowing time resulted in relatively high yield, and hence high GEY of the system. In addition, introducing mungbean into rice-wheat rotation provides additional benefits on the productivity of system (~15% higher of GEY than the rice-wheat-fallow system) due probably to its ability to fix N in the soil and its water demand is comparable with the residual water left after the previous crop.

The low productivity of the rice-fallow-rice system was strongly related to climate conditions (rainfall, average daily temperature and radiation), especially during the growing season of the second rice crop. The rainfall and average daily temperature in particular the minimum temperature of the second rice crop (November-April) was much lower than the first rice crop (June-November) (Figure 1b). The germination and establishment of the second rice crop was impaired due to cold damage (8.5^{o}C), causing crop failure (George et al., 1992; Lee, 2001). As a consequence the GEY of the system was comparatively low. This system was also considered as a riskiest system due to its high probability resulted in low GEY.

The rice-wheat-fallow system with transplanted and direct-seeded rice showed the narrowest distribution of GEY, showing less variation in GEY and hence tended to be a stabile system. The sequence of rice-wheat-fallow allows higher stability of GEY and improves resilience to different environmental constraints.

For Karnal and Patna an improvement of the system by including mungbean presented higher GEY than fallow and changing to wheat for the second crop is less risky than a double rice due to cold stress during crop establishment resulting to higher probability of crop failure.

c) Aduthurai

The rice-wheat-mungbean system showed the highest performance with 80% of the seasons resulting in GEY >168 and >144 GJ ha^{-1} with transplanted and direct-seeded rice respectively in Aduthurai (Figure 5a-b). The rice-wheat-cowpea system performed the lowest productivity with 80% of the seasons resulting in GEY <74 and <64 GJ ha^{-1} with transplanted and direct-seeded rice respectively. Comparing to the rice-fallow-rice (reference) system, Aduthurai would achieve higher GEY around 6-72 GJ ha^{-1} 80% of the seasons dependent of rice establishment by practicing the rice-wheat-mungbean system. The right crop selection and sowing time, which was tailored to the seasons, had resulted in high GEY of rice-wheat-mungbean system in this site. Similar to Karnal and Patna, the inclusion of mungbean in the rice-wheat system tended to increase high GEY of the system (~19% higher than the rice-wheat-fallow system). On the other hand, the inclusion of cowpea in the rice-wheat-cowpea system did not increase system productivity (~44% lower than the rice-wheat-fallow system). The low GEY of the rice-wheat-cowpea system was due possibly to that the system was a low inputs system with lower irrigation and fertilizer amount compared to the rice-wheat-mungbean system. Consequently the GEY of rice, wheat and cowpea was low, resulting low GEY of the system. The reason why the rice-wheat-cowpea system received comparatively low inputs because of low value of the cowpea compared to mungbean.

The rice-wheat-mungbean system had the narrowest distribution of GEY, showing less variation in GEY. The sequence of rice-wheat-mungbean provides greater stability than the other sequences, indicating more resilient on change in environmental conditions. The rice-wheat-cowpea and the rice-maize system were considered as the riskier system as they showed higher probability resulted in low GEY compared to the reference system. The low productivity of the rice-maize system was due to a low GEY of the rice crop. Rainfall during the rice growing season (July-November) was much lower than during the maize growing season (November-May) (Figure 1c). In Aduthurai, the rainfall pattern is different to other sites, it was much lower from July to October than from November to March. Whilst, in Karnal, Patna and Gazipur the rainfall was higher from July to October compared to November to March. As the rice crop is generally sown during November to April, an option was therefore proposed by switching the calendar (sowing time) with additional irrigation applied. This may indicates that the system has to be tested with different irrigation amount during the rice growing season.

d) Gazipur

Moving east to Gazipur, Bangladesh, the rice-fallow-rice system showed the highest productivity. In this system, 80% of the seasons resulted in GEY >130 and >153 GJ ha^{-1} with transplanted and direct-seeded rice respectively (Figure 6a-b). The productivity of the rice-maize system was the lowest and considered as a riskiest system with 80% of the seasons resulting in GEY <89 and <94 GJ ha^{-1} with transplanted and direct-seeded rice respectively. In this site, climate provides optimum conditions for rice to grow during the rainy and dry winter season, resulting high GEY of the system. It seems that the fallow phase in this system has to be maintained.

The low productivity of the rice-maize system in this site was due to the low GEY of the maize crop, which was greatly influenced by rainfall and average daily temperature. During the maize growing season (November-May), the rainfall and average daily minimum temperature was lower compared to the rice growing season (July-November) (Figure 1d). Further, the maize crop was set under rainfed condition, whereas the rice crop was set under irrigated condition, thus resulting low GEY of the maize crop. In addition, immediately after rice harvest, maize crop may front the risk of waterlogging during emergence and seedlings establishment, causing poor growth and lower yield, hence resulted in low GEY of the system (Timsina et al., 2010). Therefore, the timing has to be improved and the system has to be tested with additional irrigation at the start of the season. This means that simulation considering potential conditions would be better to really assess this system.

Similar to Aduthurai, the sequence of rice-wheat-mungbean showed less variation in GEY, providing greater stability than the other sequences, showing more resilient on change in environmental conditions.

Across all sites, Aduthurai and Gazipur were more productive than Karnal and Patna. The high productivity of systems in Aduthurai and Gazipur was strongly influenced by the climate conditions in particular rainfall and temperature. Rainfall and temperature were much higher in Aduthurai and Gazipur compared to Karnal and Patna (Figure 1a-d), allowing optimum condition for emergence, crop establishment and growth.

The rice-wheat-mungbean system showed high productivity at all sites (Table 4), indicating that the system is good to be implemented. This result is in line with the results of two years studies at Karnal and Patna (Gathala et al., 2013; Laik et al., 2014). The inclusion of mungbean showed positive effects on the productivity of the whole system. The rice-fallow-rice system resulted in low productivity, particularly for the sites with semi-arid and sub-tropical humid of climate such as Karnal and Patna. In these sites, the growth of second rice crop was limited due to cold temperature. The rice-wheat-cowpea and the rice-maize system performed the lowest productivity in Aduthurai and Gazipur respectively. The low productivity of rice-wheat-cowpea system was closely related to lower rainfall during the rice crop growing season, whereas the low productivity of rice-maize system was influenced by lower rainfall and temperature during the maize growing season. The crop selection and sowing time should therefore be tailored to prevailing climatic conditions.

The system productivity under direct-seeded rice conditions can be as beneficial as transplanted rice, regardless the crop sequence. This finding is consistent with the result of Yadav et al. (2011) and Gathala et al. (2013). A proper rice variety, integrated weed management and optimal irrigation were the three factors which contributed to the success of direct-seeded rice. In this experiment, suitable rice varieties and sufficient water during rice growing season also tended to be the major reasons for the higher GEY of direct-seeded rice.

Direct-seeded rice is an optimal option for rice production under less water availability and labor scarcity (Kumar and Ladha, 2011). Besides, it allows faster and easier sowing of rice, earlier crop maturity (by 7-10 days) and requires less water during crop establishment (Balasubramanian and Hill, 2002). Several factors such as short season of rice crop varieties, adequate water in particular at later growth stages and soil conditions are needed to make direct-seeded rice adapted in the system (Liu et al., 2014). Further investigation is required to capture the effect of residue, to identify effect of changes in irrigation availability on rice-based cropping systems and to assess the performance of the systems using short season varieties of main or inter-season (legume) crops.

5. Conclusions

The objectives of this study were to calibrate and evaluate the APSIM-ORYZA model to simulate rice-based cropping systems considering alternative options to fallows with non-rice crops and to investigate productivity of intensification options improving productivity of systems in South Asia using long-term simulation. This study has shown that the APSIM-ORYZA model adequately simulates diverse rice-based cropping systems grown at a range of management practices and agro-climatic conditions in IGP India, Tamil Nadu and Bangladesh. The validation testing has identified that the model is performing well at diverse crop sequences, rice establishments and residue treatments.

The simulation results confirm the importance of intensification options by improving productivity with non-rice crop during fallow. The scenario analysis presented the advantages of the intensification options moving from fallow and with direct-seeded rice. The productive sites (Aduthurai and Gazipur), which considerably have higher rainfall and temperature showed high GEY for all systems. The rice-wheat-mungbean system performed the highest productivity and was readily adapted at all sites. The lowest and riskiest system productivity (Karnal and Patna: the rice-fallow-rice; Aduthurai: the rice-wheat-cowpea; Gazipur: the rice-maize system) were closely related to climatic conditions. The low rainfall and minimum temperature as well as inappropriate crop selection and sowing time had contributed to the low GEY of systems. Further investigation is required to explore effect of changes in irrigation availability on rice-based cropping systems and to assess the performance of the systems using short season varieties of main or inter-season (legume) crops. As the model was not able to simulate the impact of residue retention over long period, further evaluation is needed with more data on residue.

6. References

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VI. General discussion

In Southeast and South Asia, the rice-based cropping systems are generally characterized with one or two rice crop per year, depending on water availability. A single rice crop is typically grown during the rainy season, whereas two rice crops are grown in areas with longer rainy season or supplemental irrigation. As water scarcity and the frequency of extreme weather events are continuing to rise, rice productivity is likely reduced in the future. In addition, soils are typically puddled and flooded during rice growing season, which may destroy soil structure and reduce organic matter, and hence decreasing soil productivity for the subsequent crops (De Datta and Hundal, 1983; Timsina and Connor, 2001).

The inclusion of legumes in the rice-based cropping system can enhance and sustain productivity due to their ability to provide N and C in the soil (Moore, 2000). Besides, legumes can improve farmers' income (Chandrasekaran et al., 1996). Other non-rice crops such as wheat and maize are also grown either pre or post-rice harvest (George et al., 1992; Singh et al., 2008). In South Asia, wheat and winter legumes are particularly grown during the cool season period as they are likely adapted to cold temperature conditions.

Intensification of rice fallow system in Southeast and South Asia is therefore challenging as the cropping system is strongly influenced by agro-climatic conditions and soil water status. Crop simulation models allow evaluation of crop performance and variability for the given management practices across agro-climatic conditions and years (Hoogenboom, 2000; Holzworth et al., 2014). The focus of this study is intensifying rice fallow system with legumes in Central Java, Indonesia and northeast Thailand (Southeast Asia), and improving of productivity of rice-based cropping system with non-rice crop during fallow in IGP India, Tamil Nadu and Bangladesh (South Asia) under diverse management practices across climatic conditions and years. The legume and/or dry season crops performance and variability in this system were assessed using validated APSIM model. In addition, factors affecting farmers using climate forecast and their perceptions of climate variability and change in rice-based cropping system in Jakenan, Central Java, Indonesia was evaluated based on the farm survey.

1. The use of climate forecast in managing lowland rice-based cropping system in Jakenan, Central Java, Indonesia

Understanding historical climate patterns and applying seasonal forecasting for responsive management will allow farmers to better manage lowland rice cropping systems. Seasonal climate forecasts (SCF) provide information that has economic value when they allow people or institutions to improve their utility from the level they would expect without the forecasts (Hill and Mjelde, 2002). This study found several factors determining the use of SCF's by farmers in lowland rice cropping system in Jakenan, Central Java. Based on data collected for this study, the factors were crop management practices, knowledge on climate forecast, and the process of decision making for farming practices (chapter II). To optimize crop production, management practices such as cultivation and irrigation management are important for dealing with the use of climate forecast. Cultivation is closely related to the availability of water irrigation and rainfall amount. Farmers are generally considered water availability to decide cropping pattern (~64% of the respondents). As the crop is particularly grown under rainfed conditions, the rainy season is therefore taken into account. This indicates that decisions on the chosen cropping pattern generally depend on the availability of water in a season.

The second factor that affects farmers in using climate forecast was their knowledge of its utility. The ability of farmers for obtaining and sharing information on climate forecasts allows them to use it for the purpose of farming practices. However, farmers are often dealing with constraints such as the timing, format of available forecast, scale and lack of expectation of the forecast (Patt and Gwata, 2002; Huda et al., 2004). Therefore, a competent guidance is required in order to use the climate forecast effectively. The last aspect that affects farmers in using climate forecasts was the process of decision making for farming practices. Farmers with easy access to climate forecast information are more likely to apply changes in their farming practices such as adjusting planting time, selection of crop variety and adjusting cropping pattern. Also, in other regions, farmers with more knowledge and skill on climate forecast respond more strongly to the forecast in regard to changing of farming activities (Rosenzweig and Udry, 2013; Abid et al., 2015).

The analysis of observed climate data at Jakenan indicated a declining trend in rainfall quantity with high annual and seasonal variability. Such findings were supported by the observations and perceptions of farmers (chapter II). In contrast their perception that the temperature had increased, observed data indicated no increase during the period 1983-2013. Other studies in Pakistan, however, show an agreement between farmers' perceptions and observed climate records (Abid et al., 2015). Whereas, studies in Ethiopia indicates that farmers' perceptions are not always in line with observed climate records (Bryan et al., 2009; Kassie et al., 2013). The difference on farmers' perceptions for temperature trend and recorded data may be due to an increase in pest and disease prevalence in recent years, causing yield reduction. It can also be due to the unclear and unpredictable information in regard to uncertain environment conditions as farmers' perceptions based on their memories over the last 20 years (Vogel & Brien, 2006). Rice production over the period 1986-2013 indicates a fluctuated and continues an increased trend after 2007, which is in line with farmers' perception. The historical data show that rice production is related to El Nino years because negative anomalies of rice production particularly occur in years when dry season rainfall below normal. Whereas farmers' perception on rice production based on the increase of drought events, which decrease dry season rainfall, causing insufficient water to irrigate crops and hence reducing rice yield.

To cope with climate variability, farmers generally adjust planting time to the onset of rainy season and select appropriate cultivars to match the season length. However, in dealing with El Nino years, the capability of farmers to use climate forecast was found to be limited. In addition, some farmers' perceptions are not supported by observed climate trends, leading to ineffective adaptation (chapter II). Therefore, to improve the productivity of rice-based cropping system in this region, farmers should be aware of the relevance of historical climate pattern and climate forecast application for responsive management.

2. Crop modelling for analysing rice-fallow system in Southeast and South Asia

Intensifying rice-fallow system with grain legumes/or dry season crops in Southeast and South Asia is a high priority to increase the productivity and sustainability of such systems. Because these are complex farming systems involving interactions between crop, soil and climate, identifying and targeting the best options is best undertaken initially with crop-soil modelling frameworks such as APSIM. Simulating such systems, using long-term climate data, may provide insights into how intensification options may perform or fit into the rotation. The APSIM framework allows incorporation of a range of agricultural variables to evaluate the impact of management practices (Keating et al., 2003; Holzworth et al., 2014). For instance, APSIM has been used to evaluate the impact of various management interventions such as inter-cropping and rotations of legumes and cereals as well as fertilizer and manure application strategies (Whitbread et al., 2010). Furthermore, models provide not only qualitative analysis of treatments but also temporal variability analysis due to climate (Keating et al., 2002), and allow evaluation of short and long-term management practices for agriculture with low cost and time requirements (Malone et al., 2007).

Well validated crop simulation models can be implemented to analyse the potential of legumes over a range of environmental and management conditions in this system. Successful calibration and validation of crop simulation models requires good quality input data such as experimental data on crop and soil management. However, to get such a good data is very rare, particularly in Asia. Another constraint, climate data on a daily time step is often missing, especially over longer time scales. Lack of data mean that field validation was not possible for Jakenan, Central Java (chapter III), but adequate data was sourced for northeast Thailand (chapter IV), IGP India, Tamil Nadu and Bangladesh (chapter V). Therefore model calibration and validation was possible with both long- and short-term field experiments respectively, providing relatively good data sets on crop, soil and climate.

The APSIM-ORYZA performed adequately in simulating the dynamics of rice phenology, grain yields and biomass in lowland rice cropping system in northeast Thailand. The model was able to predict grain yield and biomass with RMSEn in % of the observed mean was 30 and 18, respectively and a good model efficiency (EF) of 0.65 and 0.79, respectively. Whereas in IGP India, Tamil Nadu and Bangladesh, the model was able to predict grain energy yield (GEY), which represent system productivity, with RMSEn of 8% and EF of 0.94 for the given diverse crop sequences, rice establishments, residue treatments and agro-climatic conditions. This result is in line with the study of Gaydon et al. (2012) and we conclude that the APSIM-ORYZA is suitable for simulate rice-based cropping systems under varied geographical locations, soil types, crop sequences and agronomic practices.

In response to residue treatment, the model is unlikely to capture the subtle differences caused by small but long-term additions of leaf litter or residues in northeast Thailand and in IGP India, Tamil Nadu and Bangladesh. As reported by Thorburn et al. (2001), decomposition rate of residue was affected by initial mass of residue. In addition, The impact of the leaf litter quality on decomposition could not adequately explained by the C:N ratio factor since the specific decomposition rate (k) may be crop-specific (Probert et al., 1998, Thorburn et al., 2001). In response to rice cropping systems and fertilizer treatment in northeast Thailand, the APSIM-ORYZA sufficiently simulated rice grain yield and biomass. Similarly, Zhang et al. (2007) and Gaydon et al. (2009) reported the capability of the model to simulate rice variables such as grain yield and biomass in response to fertilizer treatments. The APSIM-ORYZA model however could not capture the dynamics of cowpea grain yield due to the limitation of field experiment data. The default variety of cowpea used in this study could not represent the local variety. For indeterminate legumes such as cowpea, the partitioning of assimilates to the grain is driven by daily rate of harvest index (HI), and represents the gradually increasing demand of new flowers and fruits (Turpin et al., 2002). The seed number is continually changing during the period of pod-set, causing difficulties in applying a constant seed number.

In general, the validated model allowed the simulation of soil, water and crops variables in lowland rice cropping systems in northeast Thailand and IGP India, Tamil Nadu and Bangladesh with adequate accuracy to capture the effect of different rice-based cropping systems over a range of management practices and climatic conditions. This results is in line with our hypothesis that well validated crop simulation models can be used to identify the potential of legumes and/or dry season crops performance over a range of environmental and management conditions.

3. Intensifying rice-fallow systems in Southeast and South Asia with grain legumes and/or dry season crops

In Southeast and South Asia, the successful intensification of rice-fallow systems with rainfed post-rice crops is determined by crop selection, post-rice soil conditions including residual soil water and rainfall. Identification of the potential of legume performance and rice cropping systems over a range of environmental and management conditions allows a better understanding of the system.

The potential of legume performance and rice sequential cropping systems over a range of environmental and management conditions in three lowland rice cropping systems in Southeast and South Asia are assessed by long-term simulation analysis. In general, the performance of mungbean in Central Java, Indonesia (chapter III) and cowpea in northeast Thailand (chapter IV) conformed to expected ranges of yield for given managements and climate conditions. The selection of mungbean follows the most common farmer practice in the fields as identified via the survey (chapter II). Farmers generally grow mungbean after lowland rice during the dry season due to its short growing period of 55 to 65 days, so that its water requirement can be balance with residual soil water left after the rice crop (Rahmianna, 2007; Radjit et al., 2014). For northeast Thailand, the selection of cowpea also follows the common farmer practice in the field, as it is known to be more tolerant to flooding (Naklang et al., 1999).

The yield of mungbean ranges from 350 to 1340 kg ha^{-1}, depending on management and site, and falling into the range of actual farmer yield of around 1.16 ton ha^{-1} (chapter III). For cowpea, depending on management, grain yield of 300 to 800 kg ha^{-1} was lower than its potential yield (1-2 ton ha^{-1}), but relatively higher than the experimental yield (chapter IV). Cowpea sown before rice show comparatively higher yield compared with a cowpea crop sown after rice. The differences in yield are influenced by rainfall patterns as the rainfall before the onset of rainy season in this region (March-April) is also higher than the rainfall at the end of rainy season after rice harvest (November-December). This trend is also observed in mungbean performance in Brebes, the site with higher rainfall, consistently yields higher, whilst, in Jakenan, the site with lower rainfall, results lower yields. High PAW at sowing strongly increased the yield of mungbean at all the sites in Central Java, and the yield of cowpea in northeast Thailand. At three sites (Brebes, Kebumen and Sukoharjo) in Central Java, a starting soil water of 70 mm achieve yield around 1000-1200 kg ha^{-1}, 80% of the time dependent of sowing time and soil type. In northeast Thailand, a starting soil water of 192 mm achieves a 300-400 kg ha^{-1} yield 80% of the time dependent of sowing time. The high PAW provides optimum soil water content for sowing resulting considerably higher yield. The supply of water from the rainfall, particularly the high rainfall allows water through the deeper soil and hence sufficient exploitation of the subsoil water contributes to the yield (Kirchhof et al., 1996). Another study about chickpea also shows similar trend, higher rainfall in the east of the region results considerably higher yield, whereas in the west of region, rainfall is comparatively lower, resulting lower yield (Whish et al., 2007). Further, a starting soil water of 100 mm would achieve yield around 1 ton ha^{-1} 80% of the time independent of sowing time.

The response of mungbean and cowpea yield to sowing time is associated with PAW and rainfall pattern. In Central Java, all sites with adequately long rainy season up to 6 months should be able to grow mungbean successfully. Sowing mungbean shortly after rice harvest will ensure sufficient establishment and root growth when the soil surface is moist. However, in this study, early sowing may impair crop germination due to waterlogged conditions, causing poor crop establishment and growth. The wet soil conditions after rice harvest at the beginning of the dry season are the major reason of poor crop germination and establishment (Lantican, 1982; Cook et al. 1995; So and Ringrose-Voase 1996). Residual soil water content in the seed zone is generally high after rice harvest, particularly with rain at the beginning of the dry season. This creates saturated soil condition, which is poorly aerated and limited oxygen supply to the seeds. As a consequence the metabolic processes during germination and crop establishment are inhibited (Corbineau and Come 1995). On the other hand, delay sowing provides soil to dry to optimum soil moisture conditions, increasing seedling emergence and root growth, resulting better crop establishment and higher yield. In addition, high rainfall during mungbean growing period enables sufficient water for crop growth. Other studies in East Java, Indonesia show that increasing delay of sowing mungbean tended to reduce yield because the drier conditions of the sites (Kirchhoff et al., 2000). The subsoil water use is higher at the late sowing, indicating crops induced to rely more on subsoil water. Moreover, it is figured in the higher root length densities and root growth in the deeper soil layer at study site.

In northeast Thailand, the yield of cowpea is different between cowpea pre- and cowpea post-rice cropping system in regard to sowing time. In cowpea pre-rice cropping system, delayed sowing shows relatively higher yield compare to early sowing. The high rainfall during cowpea growing period provides sufficient soil water content for the crop growth so that the use of subsoil water is limited, whereas in the early sowing, crops strongly use soil water stored because of insufficient rainfall. Consequently, crops suffer from water stress, inhibiting the imbibition, delaying germination and emergence, and hence resulting poor crop establishment (Rahmianna, 2007). In cowpea post-rice cropping system, the early sowing presents relatively higher yield than the late ones. The low rainfall after rice harvest cannot compensate soil water demand for crop growth. The crop therefore used soil water stored. To summarize, the yield of legumes in lowland rice cropping systems in

Southeast Asia is strongly affected by rainfall, soil water at sowing and sowing time. Low rainfall together with poor soil moisture and poor soil structure conditions after rice puddling in this system is likely to reduce yields. The successful of legume performance in this system should take all these factors into account.

The performance of diverse rice-based cropping systems for given management and climate conditions allows intensification options to reduce fallow in IGP India, Tamil Nadu and Bangladesh (chapter V). The rice-wheat-mungbean system was considered as the best system as it showed high productivity (grain energy yield) and readily adapted at all study sites. This system would produce grain GEY around 121-202 GJ ha^{-1} 80% of the time dependent of rice establishment. On the other hand, the rice-fallow-rice system performed the lowest productivity with 80% of the time resulted in GEY 39-60 GJ ha^{-1} in Karnal and Patna, whereas in Aduthurai and Gazipur, the lowest system productivity was the rice-wheat-cowpea (91-113 GJ ha^{-1}) and the rice-maize (103-109 GJ ha^{-1}) system, respectively. Compared to the rice-fallow-rice (reference) system, the GEY of rice-wheat-mungbean system increased by 165-191; 114-125; and 6-72 GJ ha^{-1} in Karnal, Patna and Aduthurai respectively. This likely demonstrates the role of crop sequences in this region. The selection of crop within the system, however, is important as it includes rainfall pattern and temperature conditions.

The high rainfall and temperature during the rainy season/kharif provides optimal conditions for rice crop establishment and growth, and hence optimizing yield. When the rainfall and temperature are much lower during the dry winter season, sowing wheat would be a good option as the crop is adapted to the cool temperature (Gupta et al., 2003). The inclusion of mungbean during the summer season fits very well into rice-wheat system. Mungbean not only fixes N in the soil, but also requires less water than other dry season crops to produce a high yield (Chadha, 2010). Therefore, including mungbean to the rice-wheat system would increase the productivity of the system.

The low productivity of the rice-fallow-rice (Karnal and Patna) and rice-maize system (Gazipur) was strongly influenced by rainfall and minimum temperature, particularly for the second crop during the dry winter season. The climate in Karnal and Patna is characterized by sub-tropical, sub-humid, warm summer, and mild cool winter (Ladha et al., 2003), the second/rabi rice therefore has to cope with cold stress due to cool temperatures. As a consequence, rice establishment is delayed, preventing cool temperatures that may reduce rice production (George et al., 1992). Further, when the temperature is below 10°C, germination is risky given the complete failure (Lee, 2001). In this study, the average minimum temperature of Karnal and Patna during the dry winter season was 7-8.5°C, resulting germination failure and hence reducing GEY of the system. Another study of rice-rice system in Jessore, Bangladesh presents a similar result that sowing boro rice in November 2012 resulted in seedlings failure due to cold damage with minimum temperature falling below 10°C in January 2013 (Ahmed et al., 2015). For Gazipur, the low productivity of rice-maize system was influenced by low rainfall and minimum temperature during the maize growing season. Besides, maize crop may be exposed to waterlogging during emergence and seedlings establishment when it is sown directly after rice harvest, causing lower yield and hence reducing productivity of the system (Timsina et al., 2010). For Aduthurai, the low productivity of rice-wheat-cowpea system was possibly influenced by sowing time, irrigation and fertilizer application. Delaying sowing of rice crop in July along with low irrigation and fertilizer amount tended to reduce yield, causing lower productivity of the system.

The lowest system productivity was also considered as the riskiest system as it showed higher probability resulted in low GEY than the reference system at all sites. On the other hand, the mungbean-wheat-fallow tended to be a stabile system in Karnal and Patna, whereas the rice-wheat-mungbean system was considered as a stabile system in Aduthurai and Gazipur. These systems showing less variation in GEY compared to the other systems, providing greater stability to deal with various environmental constraints.

Across all sites, each rice sequential cropping system showed comparatively high GEY in Aduthurai and Gazipur, while in Karnal and Patna, the rice-fallow-rice and the rice-maize system performed low GEY. Aduthurai and Gazipur therefore tended to be more productive than Karnal and Patna. Aduthurai and Gazipur have higher rainfall compared to Karnal and Patna. This is also true for minimum and maximum temperature. The temperature is higher in Aduthurai and Gazipur than in Karnal and Patna. These climatic conditions make the Aduthurai and Gazipur more favorable for diverse rice-based cropping systems.

Regardless of crop sequence, system productivity with direct-seeded rice was relatively higher than transplanted rice. This indicates that direct-seeded rice can be as favorable as transplanted rice. Field experimental studies in India (Yadav et al., 2011;

Gathala et al., 2013) and China (Liu et al., 2014) also showed similar results. Suitable rice varieties and adequate water during rice growing season likely influence the higher GEY of direct-seeded rice. In addition, direct-seeded rice allows faster and easier sowing of rice, earlier crop maturity (by 7-10 days), requires less water during crop establishment and higher tolerance to water deficit, and reduces labor requirements (Balasubramanian and Hill, 2002). This study in South Asia highlights the need of crop selection to identify suitable non-rice crops which can fit in the agro-climatic condition within rice-based cropping system.

4. Conclusions

The survey study was set out to identify factors affecting farmers using climate forecast in lowland rice-based cropping system in Jakenan, Indonesia and farmers' perceptions of climate variability and change. The simulation study was arranged to intensify rice-fallow systems in Southeast and South Asia with grain legumes/or dry season crops using simulation analyses. Simulation allowed the evaluation of a very complex cropping system including a series of interaction of crop, soil, climate and management practices over a long time period. Whereas the field experiments are generally conducted for a short time period and limited to capture spatial and temporal variability related to climate. The APSIM-ORYZA model has demonstrated its strength in simulating the performance of rice crop for the given treatment application and climate variation in Southeast Asia, and the performance of rice-based cropping system over a range of crop sequences, rice establishments, water management and fertilizer application across agro-climatic conditions in South Asia. However, the model was unlikely to capture the effect of residue retention in the system.

The factors affecting farmers using climate forecast information in lowland rice cropping system in Central Java, Indonesia are management practices, knowledge of climate forecast and the process on decision making for farming practices. Farmers' perceptions of climate variability and change are influenced by rainfall variability, and have changed farming practices through adjustment of planting time, selection of crop variety and adjustment of cropping pattern.

The performance of legumes in two lowland rice cropping systems is confirmed to expected ranges of yield for given management and climatic conditions. Soil water at sowing, rainfall and sowing date were identified as the main determinants of yield.

Mungbean sown at late sowing with a starting PAW of 70 mm at sowing had an 80% probability of producing yield as high as farmer actual yield (chapter III). Cowpea sown before rice crop at early sowing with a starting PAW of 192 mm at sowing had an 80% probability of producing yield around 300-400 kg ha^{-1} (chapter IV). Successful legumes production in lowland rice-based cropping systems should take rainfall, soil water at sowing and sowing date into account. Further evaluation is required to analyse intensification of the fallow phase on rainfed lowland rice with different cultivars or legumes species.

The scenario analysis demonstrated the advantages of the intensification options moving from fallow and with direct-seeded rice in IGP India, Tamil Nadu and Bangladesh (chapter V). The rice-wheat-mungbean system showed the highest productivity and was readily adapted at all sites. The lowest and riskiest system productivity (Karnal and Patna: the rice-fallow-rice; Aduthurai: the rice-wheat-cowpea; Gazipur: the rice-maize system) were strongly influenced by climatic conditions. The system productivity under direct-seeded rice conditions can be as beneficial as transplanted rice, regardless of crop sequence. Selection of option improving productivity in rice-based cropping system is strongly affected by climate conditions such as rainfall and minimum temperature. Further investigation is required to assess the performance of the system through changes in irrigation availability and using short season of main or legume crops. In addition as the model was unlikely to capture the effect of residue retention over long periods of time, detail of residues data sets would be required for further evaluation of the model simulation.

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Summary

In most Southeast and South Asia countries, lowland rice is particularly grown as a single crop at the wet season, followed by dry season crops or fallow at dry season and characterized under rainfed condition. The inclusion of dry season crops such as legumes into rice based cropping system has contributed to improve soil structure and nutrition, providing the basis for rice yield enhancement. In addition, dry season crops require less water in comparison to rice and are therefore better options for additional income.

The success of the dry season crops generally rely on climatic conditions prevailing during crop establishment stage and various management practices. Since rainfed lowland rice highly depends on the reliability and amount of rainfall, the growth of the subsequent crops can be restricted due to low and erratic rainfall, as a result they rely on residual moisture from the wet season crop. Besides, undesirable climatic condition such as droughts and floods can lead to increased risk of crop losses. The poor performance of dry season crop is also influenced by limited inputs and management as well as limited research and extension advice. As a consequence, the crops receive low inputs and management level along with the adverse soil moisture and soil structure conditions which contribute to the low yields.

To meet the yield of dry season crops, the crop establishment has to be improved and residual soil water during the period after rice crop has to be maintained. The success of crop establishment can be achieved by rapid germination, which relies on the content of soil water and the contact between seed and soil. An approach is also required to improve understanding of the impact of climatic variation, which allows farmers to respond to climatic variability and possible future climate change.

In regions with high rainfall, farmers are mostly postponing planting or providing surface drainage in order to avoid waterlogging. The correct planting time of crops and the availability of subsoil water are related to climatic conditions, which determine the success of the crops. Since planting time is important for the success of dry season crops, the planting window is therefore narrow and will be defined by interaction between the crop growth and environmental condition.

Many studies showed that management system such as planting time adjustment, water management, and tillage can be used to maximize dry season production, nevertheless they are time consuming and expensive. Simulation studies could therefore be useful to interpret the interaction between soil, crops, management

options and weather in rice cropping system. Modeling is able to explain the correlation among the components of complex systems, give more insight into processes and verify the consequences of management as well as explore the potential for modification. The application of appropriates model to simulate rainfed lowland rice cropping systems is a challenge, especially related to climate variability. The Agricultural Production Systems Simulator (APSIM) cropping systems model, which has been developed by Agricultural Production System Research Unit in Australia, has the ability to simulate diverse cropping systems, rotation and environmental dynamics.

Information on how to intensify rice-fallow systems in Southeast Asia is limited. Therefore, the main objective of this study was to intensify and analyse rice-fallow systems in Southeast (Indonesia and Thailand) and South (IGP India, Tamil Nadu and Bangladesh) Asia with grain legumes/dry season crops, using field experiment and simulation (chapter I). The second chapter examines the effective use of climate forecast information, farmers' knowledge and ability in understanding and predicting the response of agricultural systems to climate variability in Jakenan, Central Java Indonesia and was based on face to face interviews with smallholder farmers, using a semi-structured questionnaire that consists of open and closed questions. The interview was conducted in four villages (Ngastorejo, Tlogorejo, Bungasrejo and Sendangsoko) in Jakenan sub-district and a total of 100 farmers were selected randomly based on the list of farmers available in each village. The findings revealed characteristics of the respondents, factors that affect farmers in using climate forecast information in lowland rice-based cropping system, and farmers' perception on climate variability and change. About 80% of respondents in Jakenan indicated rice-rice-mungbean as their main cropping pattern. Selection of cropping pattern is mostly based on water availability. To meet crop water requirements, farmers usually apply supplemental irrigation over rice growing season. Looking at current climate variability and change, the use of climate forecast is important to improve crop production and to cope with climate risk. According to the survey about 70% of respondents have knowledge of climate forecast and use it for planting time determination. Adjusting sowing time and selection of appropriate crop varieties has become their main strategy in coping with climate variability. Farmers' adoption level however was low considering climate risk management especially coping with El Nino events.

In the third chapter, the opportunity of legumes performance at various sowing times, residue treatments, soil types and plant available water at four sites in Central Java, Indonesia is presented. The performance of the model for growing legumes under different agro-climatic conditions in rainfed lowland rice system is also evaluated. Results from long-term scenario analysis showed that late sowing at 70 mm of plant available water is crucial factors for greater yields of mungbean across all four sites. Across the four sites, different sowing time and plant available water had effect on mungbean yields. Delay sowing at 70 mm of plant available water in dry season will ensure better establishment because soil is not very wet and well-structured and drained so that the emergence and root growth is not inhibited, resulting greater yields. The site with adequate rainfall at the end of dry season should be able to grow mungbean effectively. To grow mungbean successfully in rainfed lowland rice-based cropping system, we should consider rainfall, soil water at sowing and sowing time.

The fourth chapter discusses the long-term potential of intensified rice/or fallows in relation to historical climate data and the opportunity and riskiness of legumes within rainfed lowland rice-based cropping system in northeast Thailand. Model evaluation indicated fairly well results for rice phenology, grain yield and biomass. The model was able to predict grain yield and biomass with RMSEn in % of the observed mean was 30 and 18, respectively and a good model efficiency (EF) of 0.65 and 0.79, respectively for the given treatment applications and inter-annual climate variations. The model however was unlikely to capture the dynamic of cowpea grain yield. Further investigation is required to use APSIM model using different legume species. The long-term simulation evaluated the opportunity and performance of cowpea sown before and after rice in rainfed lowland rice-based cropping system in northeast Thailand. Results indicated that cowpea sown before or after rice cropping was influenced by rainfall, soil water at sowing and sowing date. Sowing cowpea in the dry season close to the onset of the rainy season will allow for reliable crop establishment and root growth as the soil surface is adequately moist. Whereas sowing cowpea in the dry season shortly after rice harvests allows suitable soil conditions to allow roots to penetrate and explore the subsoil water, contributing towards good crop establishment and growth. The ability of the model to simulate such a system can provide useful information for farmers and be used to simulate the benefits and risks of using different legumes species.

The last chapter presents the capability of the APSIM-ORYZA in simulating diverse rice-based cropping system over a range of management practices and agro-climatic conditions in South Asia (IGP India, Tamil Nadu and Bangladesh). The validation model was able to predict grain energy yield (GEY), which represent system productivity, with RMSEn of 8% and EF of 0.94 for the given diverse crop sequences, rice establishments, residue treatments and agro-climatic conditions.

The long-term scenario analysis demonstrated the beneficial of the intensification options with non-rice crops and direct-seeded rice. The rice-wheat-mungbean system showed the high GEY and was simply adapted at all study sites. The lowest and riskiest system productivity (Karnal and Patna: the rice-fallow-rice; Aduthurai: the rice-wheat-cowpea; Gazipur: the rice-maize system) showed higher probability of climatic risk. Selection of option improving productivity in rice-based cropping system is strongly affected by climate conditions such as rainfall and minimum daily temperature. Regardless crop sequence, the GEY of system with direct-seeded rice was relatively higher than transplanted rice, indicating that direct-seeded rice can be advantageous as transplanted rice. The success of direct-seeded rice in this study was possibly due to suitable rice varieties and sufficient water during rice growing season. Further investigation is needed to identify effect of changes in irrigation availability and to evaluate the performance of the systems using diverse short duration varieties of main or legume crops. Evaluation of the effect of residue retention is also required, particularly for long period of time using more data on residue.

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D E C L A R A T I O N S

1. I, hereby, declare that this Ph.D. dissertation has not been presented to any other examining body either in its present or a similar form. Furthermore, I also affirm that I have not applied for a Ph.D. at any other higher school of education.

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2. I, hereby, solemnly declare that this dissertation was undertaken independently and without any unauthorised aid.

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