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Agro-ecology of rice-based cropping systems

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Preface

This volume presents research proceedings of the SARP theme 'Agro-ecosystems' in 1992 - 1993. Most of the papers are a selection of presentations that were given on the 'International Workshop on Agro-ecological Zonation of Rice', hosted by the Agro-ecology Institute of the Zhejiang Agricultural University at Hangzhou, P.R. of China, 14 - 17 April 1993. At this Workshop, two days were devoted to the special topic of agro-ecological zonation and agro-ecosystems, and one day was devoted to a meeting of all SARP team leaders. Halfway the workshop, a field trip to the ecological farm at Fushang was organized. The Agro-ecology Institute of the Zhejiang Agricultural University is gratefully thanked for having hosted the workshop. Especially the SARP team supervisor and director of the Agro-ecology Institute, professor Wang Zhaoqian, and his SARP team have put much effort in the organization and smooth course of the workshop. A full list of participants is given at the end of this book. The SARP theme leaders of Agro-ecosystems, dr F.W.T. Penning de Vries of CABO-DLO and dr M.J. Kropff of IRRI have contributed much to the planning and scientific guidance of the theme in general.

Most papers in this volume deal with the application of simulation modelling and systems analysis in extrapolating research findings from field experimentation to larger - regional to national - scales and to different agro-ecological environments. Though most authors focus on rice production, other crops such as corn (Wan Sulaiman & Singh), wheat (Sattar) and paulownia-wheat intercropping (Wu) are considered as well. In the first paper the use of simulation modelling in rice cropping optimization is illustrated by quantifying the relationships between rice yield and irrigation water needs on the one hand and weather, soil and management practices on the other (Bouman et al.). In the following papers, simulation modelling is used to explore irrigated and rainfed crop production potentials as a function of agro-ecological environments in a number of countries in Asia: Thailand (Pannangpetch), Philippines (Wopereis et al.; Garcia; Lansigan & Orno), Malaysia (Wan Sulaiman & Singh), Bangladesh (Bhuiyan & Ahmed; Sattar), Indonesia (Makarim & Las), China (Yang & Zhang), and India (e.g. Ramaswami & Selvaraju; Thiyagarajan et al.). In many of these papers, crop growth durations, optimum sowing and transplanting dates and cut-off dates were determined as well because of their importance in planning and optimizing cropping sequences. Four papers address the combined use of crop growth simulation models and Geographic Information Systems (GIS) in quantifying and mapping regional crop production levels (Pannangpetch; Wopereis et al.; Bhuiyan & Ahmed; Garcia). Two papers address the specific problem of quantifying the uncertainty and variation in model input parameters (soil, weather) on regional scales, and their impact on simulated crop production (Bouman; Lansigan). The last five papers are all devoted to the agro-ecology - and the use of crop growth simulation modelling therein - of Tamil Nadu state in southern India (Palaniappan et al.; Budhar & Palaniappan; Ramaswami & Selvaraju; Thiyagarajan et al.; Jeyaraman et al.).

Contents

Application of simulation and systems analysis in rice-cropping optimization

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Abstract
The use of crop growth simulation modelling and systems analysis was demonstrated in the exploration of the effects of weather and soil on rice cropping. The growth model ORYZA_W, as developed in the SARP project (Simulation and Systems Analysis for Rice Production), simulates rice growth in irrigated lowland and rainfed upland environments. The effect of climate (radiation, rainfall, temperature) and soil characteristics (texture, seepage and percolation rates) on rice yield and irrigation requirement was explored for a case-study at Patancheru (Hyderabad, India). Risk analysis was performed on weather, sowing date and soil type. The results are useful in designing and optimizing cropping strategies and irrigation systems in different agro-ecosystems. Crop characteristics for regional application (such as the case study presented here) should be derived for locally used varieties, and the simulation model should be well validated under the environmental conditions at the region under study.

Introduction

It is estimated that global rice production must increase by 65% by 2020 to keep up with expected population growth (IRRI, 1993). In India, the estimated food requirement to feed 1 billion people in the year 2000 is about 225 million tonnes (Budhar & Palaniappan; 1993). This means that an additional 75 billion tonnes has to be produced within the next decade (an increase of 50%). Since most of the potentially suitable, and in some cases even marginally suitable, land has been brought under production in the past years, increases in production have to come from increased yield levels. A complicating factor to increase yield levels is that agricultural resources and inputs are becoming scarce in many places. Ground water levels and river water supplies are decreasing alarmingly in some places due to agricultural over-exploitation and/or competition with industry and cities. Salinization threatens the sustainability of irrigation systems. To reach increased productivity in the long term, natural (climate, soil) and human (management) resources have to be fully mobilized and exploited on a sustainable basis. In order to develop appropriate farming technologies, it is essential to have an understanding of the potentials of crops and cropping systems at given agroclimatic environments. Simulation and Systems Analysis are powerful tools to gain insight in the complex eco-physiological processes of crop growth, and to extrapolate experimental results to larger scales and to different agro-ecological environments.

To spread and further develop knowledge about simulation and systems analysis in Asia, the SARP project (Systems Analysis and Simulation for Rice Production) was started in 1984 (ten Berge, 1993). SARP was jointly initiated by the Centre for Agrobiological research (CABO-DLO) and the Department of Theoretical Production Ecology of the Wageningen Agricultural University (WAU) in Wageningen, The Netherlands, and by the International Rice Research Institute (IRRI) in The Philippines. In the first phase of the project (1984 - 1987), teams at 16 National Agricultural Research Centres (NARCs), of which five teams from India, received training. During the second phase (1987 - 1991), collaborative research developed as a follow-up on case-studies conducted in the training program (Penning de Vries et al., 1991). The current third phase (1992 - 1996) aims to consolidate the teams of rice researchers at the NARCs and to develop and execute a joint research program formulated by the NARCs, IRRI, CABO-DLO and the WAU. Collaborative research in SARP is concentrated in four themes: agro-ecosystems, potential production, crop and soil management, and crop protection. One of the main research issues in the agro-ecosystems theme is agro-ecological zonation and cropping systems optimization. This paper will demonstrate the possibilities of simulation and systems analysis, as developed in SARP, to quantify the relationship between (rice) crop growth and environmental variables (soil, weather), and for the assessment of rice yield potentials and risks in various agro-ecological environments. A case-study using weather data from Patancheru (Hyderabad), India, will serve as illustration.

Material and methods

The agro-ecological rice growth model ORYZA_W

The rice growth model ORYZA_W simulates the growth and development of rice in irrigated lowland and in rainfed upland environments (Bouman, 1993). In a lowland environment, rice is either direct-seeded or transplanted in puddled soil. In an upland environment, rice is direct-seeded in non-puddled (ploughed or harrowed) soil. The above-ground part of ORYZA_W, i.e. the actual growth model, is the model ORYZA1 as developed and described by Kropff et al. (1993). ORYZA1 is based on earlier models such as MACROS L1D (developed in the first phase of SARP; Penning de Vries et al., 1989) and SUCROS (van Laar et al., 1992) and was further elaborated from rice experiments at IRRI. ORYZA1 simulates crop growth under irrigated conditions, with optimum supply of nutrients (except N that is explicit input as leaf-N content), and without pest and disease infestation. A summary description of ORYZA1 is given by Kropff et al., 1992:

'Under favourable growth conditions, light and temperature are the main factors determining the growth rate of the crop. From the leaf area index of the species and the vertical distribution of leaf area, the light profile within the canopy is calculated. On the basis of single leaf photosynthesis, which depends on the N concentration, the photosynthesis profile in the full canopy is obtained. Integration over the height of the canopy and over the day gives the daily assimilation rate. After subtraction of respiration requirements and accounting for losses due to the conversion of carbohydrates into structural dry matter, the net daily growth rate in kg ha^{-1} d^{-1} is obtained. The dry matter produced is partitioned among the various plant organs. Phenological development rate is tracked in the model as a function of ambient mean daily air temperature. When the canopy is not yet closed, leaf area development is calculated from mean daily temperature. When the canopy closes, the increase in leaf area is obtained from the increase in leaf weight. Calculation of the net daily growth rates combines the dry weight increase of leaves, stems, and grain based on a partitioning coefficient that depends on the stage of phenological development. Input requirements of the model are: geographical latitude, standard daily weather data (radiation, minimum and maximum temperature), plant density, date of sowing, and parameter values that describe the morphological and physiological characteristics of the plant species. The time step of integration is one day.'

ORYZA1 was calibrated and validated using a number of experiments conducted at IRRI (Kropff et al., 1993) (Figure 1). To realize potential yields, nitrogen (N) gifts were very high to ensure a good leaf-N status throughout the growing period. E.g. in the dry

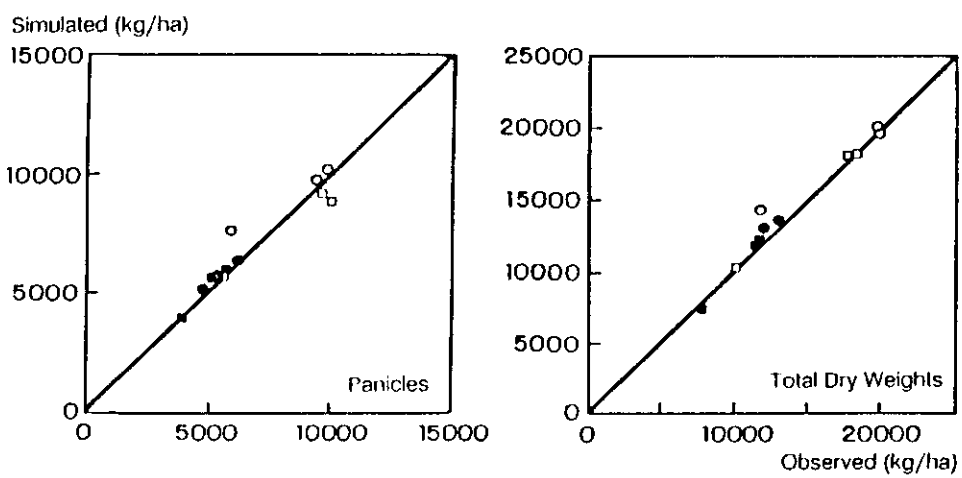

Figure 1. Simulated versus measured dry biomass of the panicles and of the whole crop of two rice varieties at three N application levels in the 1991 wet season and the 1992 dry season, IRRI (taken from: Kropff et al., 1993).

season of 1992, the highest N treatment was 225 kg ha^{-1} (2 splits before panicle initiation and 45 kg ha^{-1} at flowering), which was 105 kg ha^{-1} higher than the current practice at IRRI. The yield of a hybrid rice (465616H) at this level of N application was 10.7 t ha^{-1}.

To compute irrigation water requirements in irrigated lowland situations, ORYZA1 was extended to calculate potential evapotranspiration based on the Penman equations (Bouman, 1993). Meteorological input for the evapotranspiration module are daily values of radiation, temperature, wind speed and relative humidity. To simulate rice growth in rainfed (water-limited) upland environments, ORYZA1 was further adapted to account for the effects of drought stress. Drought stress reduces the daily total gross CO_2 assimilation rate and changes the carbohydrate partitioning of the crop (Penning de Vries et al., 1989). The amount of drought stress is expressed as the ratio of actual over potential transpiration. As yet, actual transpiration in the model is reduced when the water content of the soil drops below saturation. There is no consensus yet in literature about the validity of this assumption (some authors have found that drought stress only occurs when the soil water content drops below field capacity), and further research is still needed. Also, the model does currently not handle extremely severe drought stress: when the carbohydrate requirement for maintenance of the crop has been larger than that supplied by photosynthesis for more than three consecutive days, the simulation of crop growth is stopped.

In ORYZA_W, the extended growth model ORYZA1 is linked with different water balance models for the different agro-ecological environments. For *lowland* environments, a simple water balance LOWBAL was developed to track the ponded water level in the paddy field and to compute the necessary irrigation requirements. Input in the model are daily values of evapotranspiration as calculated in the extended ORYZA1, daily rainfall, bund height, depth of puddled layer and seepage and percolation (SP) rate. The SP rate is a constant which has to be measured in the field from e.g. sloping gauges. Timing and amount of irrigation can be varied by the model user. LOWBAL was validated for irrigated lowland conditions with field experiments at IRRI (Bouman et al., 1993) (Figure 2). For *upland* environments, the water balance SAHEL (Penning de Vries et al., 1989) was used to simulate the soil water content in freely draining soils (deep ground water table; no stagnating surface water). Main input in the model are daily values of evapotranspiration, as calculated in the extended ORYZA1, daily rainfall, rice rooting depth and four key points on the pF curve of the soil: water content at saturation, at field capacity, at wilting point and at air-dryness.

A user-friendly interface, called the SARP-Shell, was developed for easy manipulation of ORYZA_W with large data sets. Interactive graphical facilities were included to quickly view simulation results.

Case study at Patancheru (Hyderabad), India

The possibilities for application of ORYZA_W in rice-based agro-ecosystems are illustrated with weather data from the ICRISAT meteorological station at Patancheru (Hyderabad), India. Seven years of daily observations (1978 - 1984) of all necessary variables (see

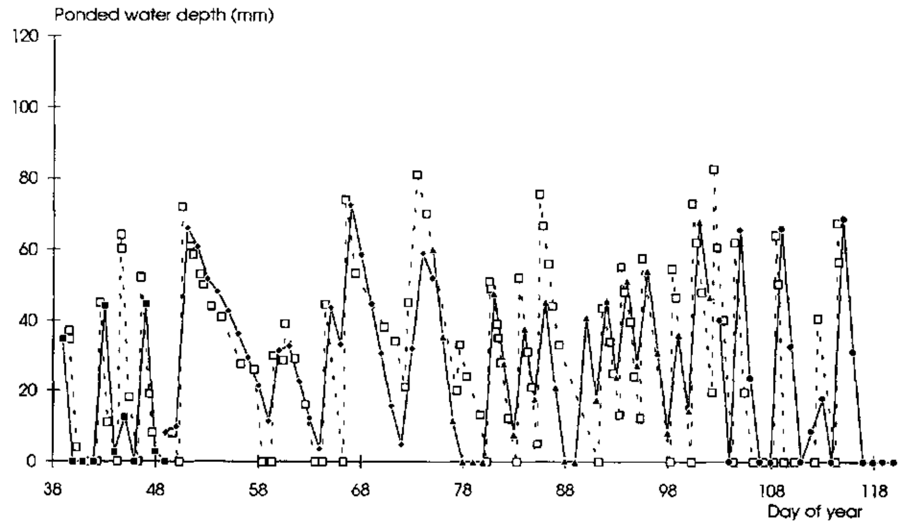

Figure 2. Observed (closed symbols) and simulated (open symbols) ponded water depth with the water balance model LOWBAL for a field trial at IRRI.

above) were available. In irrigated lowland environments, crop growth was simulated for soils with different SP rates. In rainfed upland environments, crop growth was simulated for soils of different texture class. Because no actual soil data for the Patancheru area were available, standard soil data were taken from Penning de Vries et al. (1989; pp. 152). In principle, crop characteristics should be derived for varieties that are used in the region, and preferable from field trials within the agro-ecological region under consideration. By default, however, crop data for this study were taken for the variety IR72 as derived by Kropff et al. (1993) from the (high N) experiments at IRRI (see above).

Results and discussion

A summary of the average weather conditions between 1978 - 1984 is given in Figure 3. Average rainfall in the June - October wet season was 822 mm, with a minimum of 630 mm in 1979 and a maximum of 1066 mm in 1981. During the rainy season, solar radiation in the visible region was lowest in August (due to the clouds). Radiation peaked in April - May. The daily temperatures were highest in April - May and lowest in December - January.

Risk analysis in irrigated lowland

Potential (rough) rice yield for IR72 in irrigated lowland environments was predicted with 30 days sowing intervals from January 1 onwards for all seven years of weather data (Figure 4). The period in the seed bed was fixed at 15 days throughout the year. Highest potential yields of 12 - 14 t ha^{-1} were obtained when rice was sown at the end of August (day 240). Lowest yields of 6.5 - 8.5 t ha^{-1} were obtained when rice was sown at the

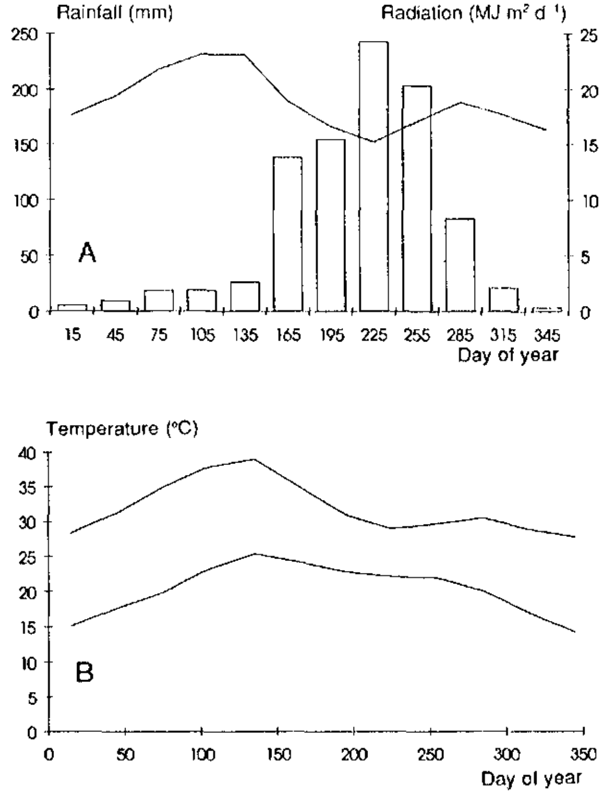

Figure 3. Monthly averages of rainfall and daily radiation (visible wavelengths) (A) and of daily minimum and maximum temperature (B) at Patancheru (Hyderabad), 1978 - 1984.

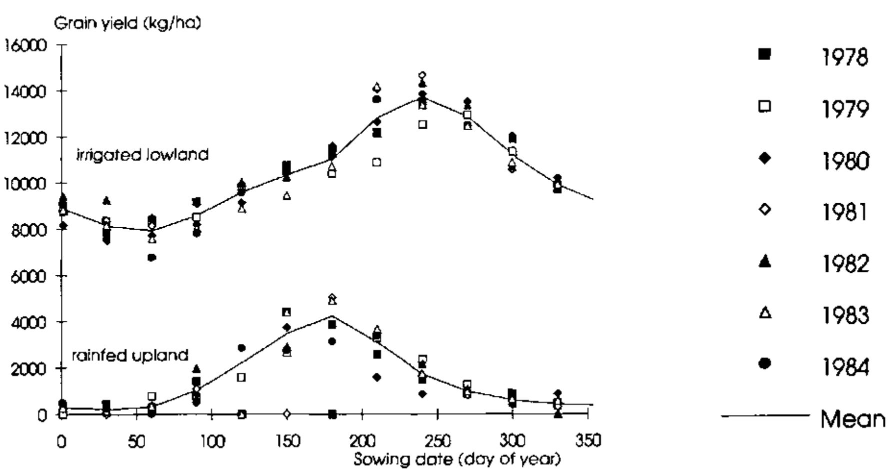

Figure 4. Predicted irrigated lowland and rainfed upland (rough) rice yield at Patancheru, 1978 - 1984.

beginning of March (day 60). It should be noted that these relatively high yields are predicted for potential production situations with no sink limitations: assuming no water limitation, optimum supply of nutrients (high N levels!) and no pest and disease occurrence. The yield differences in Figure 4 are mainly explained by the variation in temperature during the year. With sowing on day 240, the crop developed during the relatively cold period, which caused a long growth duration of about 150 days on the average. With sowing on day 60, the crop developed at increasing temperatures and the average growth duration was only some 110 days. A short growth duration means relatively little time for grain filling, and hence a relatively low yield. Even the high levels of solar radiation after day 60 (Figure 3A) could not compensate for the yield-reducing effects of high temperatures with sowing on day 60.

The highest yields actually realized at Patancheru are reported to be around 12 t ha^{-1} (Virmani, ICRISAT, pers. com.). The relatively high levels of simulated maximum yields (12 - 14 t ha^{-1}) may be explained by the fact that ORYZA1 simulates potential rice yield with no sink limitations; effects of low and/or high temperatures on spikelet sterility are not included. When rice is sown around day 240, flowering occurs during a period where the minimum temperature can drop to 15 °C and less (Figure 3B). Shouichi Yoshida (1981; pp. 72) has reported that 'temperatures below 20 °C at about the reduction division stage of the pollen mother cells usually induce a high percentage of spikelet fertility (Satake, 1969)'.

The total irrigation requirements for the crop with different sowing dates in Figure 4 are given in Figure 5. A quantity of 200 mm was assumed to be needed for land preparation and puddling, and a constant gift of 50 mm was applied each time that the level of standing water in the field dropped below 10 mm (common values encountered in irrigation

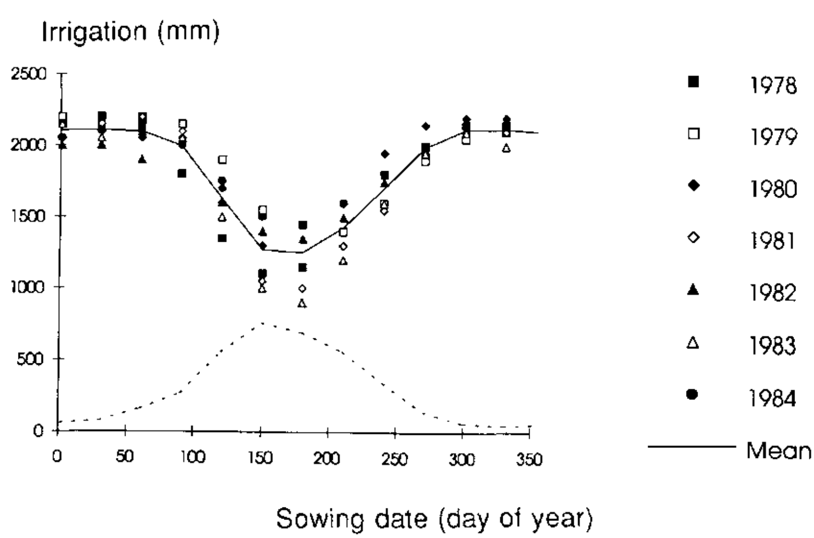

Figure 5. Irrigation requirements for lowland rice at Patancheru, for the same crop with different sowing dates as in Figure 4. The accumulated rainfall during the growing period is given by the broken line.

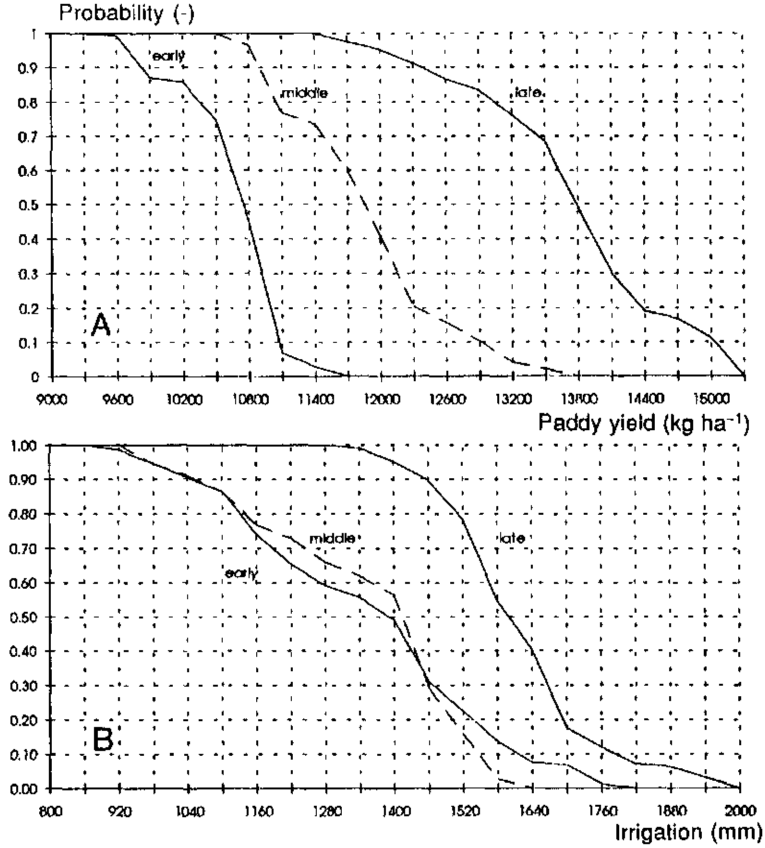

Figure 6. Exceedance probability of irrigated (rough) rice yield (A) and irrigation requirements (B) of lowland rice at Patancheru, 1978 - 1984. Early sowing was between days 140 - 160, middle sowing between days 180 - 200, and late sowing between days 220 - 240.

schemes). The SP rate was 5 mm d^{-1}. Irrigation requirements were highest when crops were sown in November-March, coinciding with the end of the wet and the beginning of the dry season. Thus, the top yields of 12 - 14 t ha^{-1} with sowing on day 240, were accompanied with the largest irrigation requirements of 2000 - 2200 mm per crop cycle. Crops sown at the beginning of the rainy season accumulated the largest amount of rainfall in the growing period and had the lowest irrigation requirements, 900 - 1500 mm. These values compare well with values generally reported in literature (e.g. Tabal et al., 1992), but should be validated with local experiments.

Risk analyses of rice yield and irrigation requirements are best illustrated with exceedance probability curves. Rice yield for the rainy season was simulated with early sowing (20 days between days 140 - 160), middle sowing (days 180 - 200) and late sowing (days 220 - 240), for all seven years of weather data (Figure 6). There was 50% probability of at least 10.8, 11.9 and 13.8 t ha^{-1} potential (rough) rice yield with early, middle and late sowing respectively. The corresponding 50% probability irrigation requirements were 1400

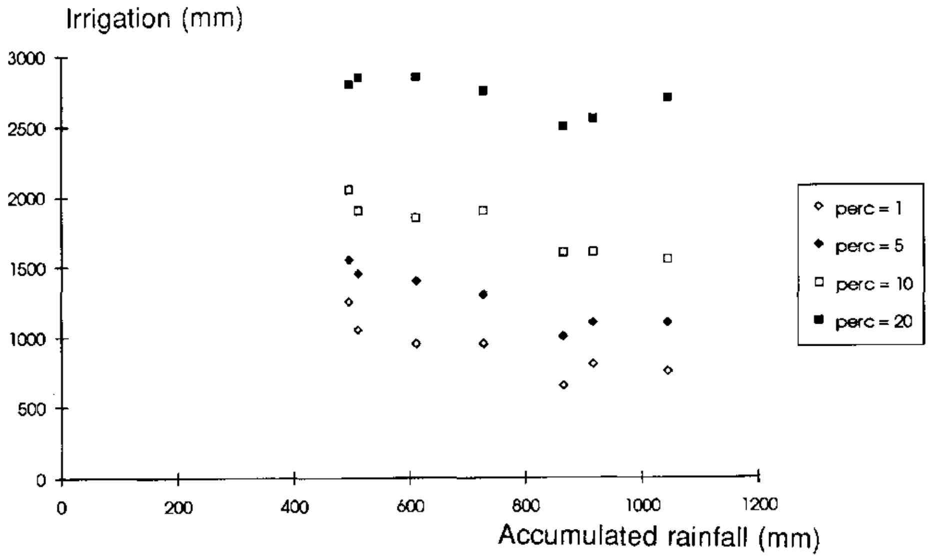

Figure 7. Irrigation requirements for lowland rice in the wet season (sowing date is day 150), Patancheru, 1978 - 1984. Soils had 1, 5, 10 and 20 mm d^{-1} seepage and percolation rate.

mm for early and middle sowing and 1580 mm for late sowing. Potential yields were most stable with early and middle sowing (the range of obtained yields was largest with late sowing). The information in Figure 6 can be useful in optimization schemes of lowland rice production and water use efficiency. E.g. if irrigation water is scarce, sowing dates in the middle of the rainy season may be one of the best options: relatively good potential crop yields are combined with relatively low irrigation requirements.

Irrigation requirements mostly depended on rainfall and on the SP rate of the soil. In Figure 7, simulated irrigation requirements are plotted against accumulated rainfall during the growing period, on soils having 1, 5, 10 and 20 mm d^{-1} SP rates. Sowing took place on day 150. With low SP rates, the relationship between irrigation requirements and rainfall was most clear: with 1 mm d^{-1} SP rate, every mm of rainfall could replace 0.8 mm of irrigation; with 20 mm d^{-1} SP rate, every mm of rainfall could only replace 0.5 mm of irrigation.

ORYZA_W is also suitable to calculate irrigation scheduling. For a given constant irrigation gift, the time of application is found in the model when the water level in the paddy field has reached a minimum (user-defined) value. In Figure 8, the timing of a 50 mm irrigation gift is plotted for rice sown on day 150 of the year 1978, on a relatively impermeable soil (SP = 1 mm d^{-1}) and on a relatively permeable soil (SP = 10 mm d^{-1}). The irrigation gifts during the first 15 days were applied to the seed bed. With 1 mm d^{-1} SP rate, the shortest interval between irrigation gifts was about 8 days. With 10 mm d^{-1} SP rate, the shortest irrigation interval was 3 days. This type of information is useful in irrigation

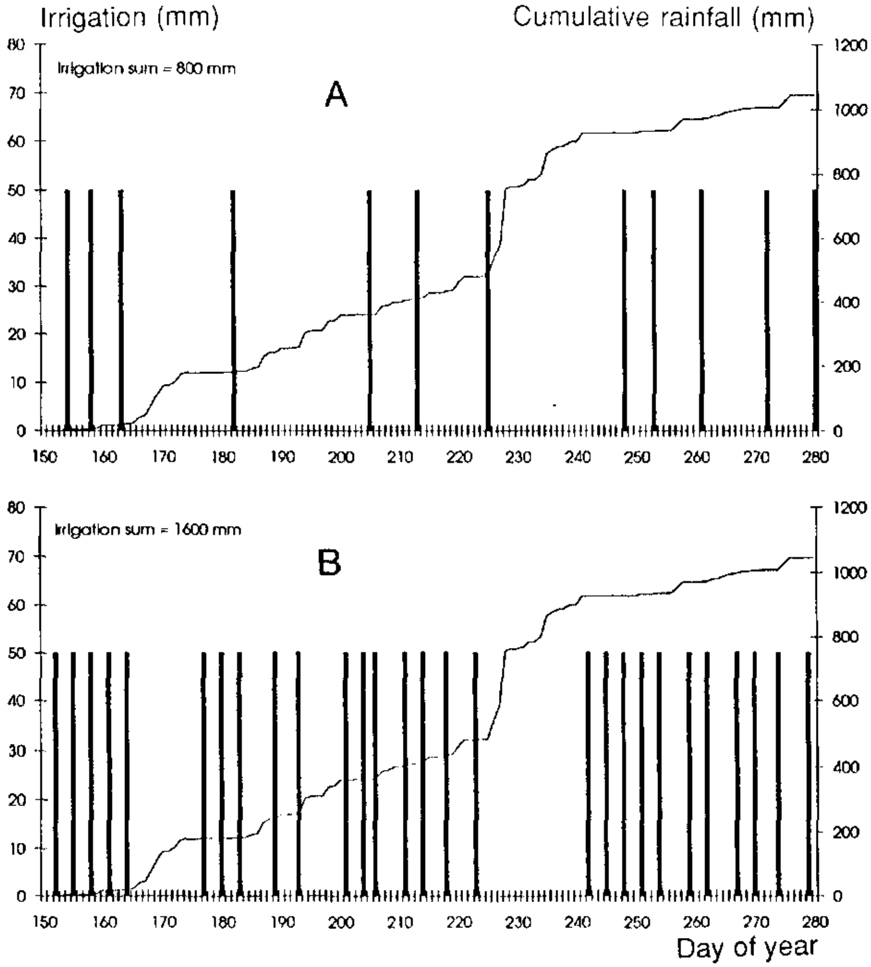

Figure 8. Irrigation timing of lowland rice in the wet season (sowing date, day 150) in 1978, at Patancheru. Seepage and percolation rate of the paddy soil was (A) 1 mm d^{-1} and (B) 10 mm d^{-1}. The cumulative rainfall during the growing period is given by the solid line.

systems design. E.g. If the time needed to irrigate the field of one farmer is about half a day, 16 farmers can be assigned to one rotation unit on the impermeable soils, and only 6 farmers on the permeable soils.

Risk analysis in rainfed upland

Rainfed upland (rough) rice yield was predicted on a loamy soil with 30-days sowing interval from January 1 onwards (Figure 4). As expected, simulated rice yields were much lower than in an irrigated lowland environment. The highest yields occurred with sowing dates at the beginning of the rainy season, days 150 - 180, fully benefiting from the rainfall

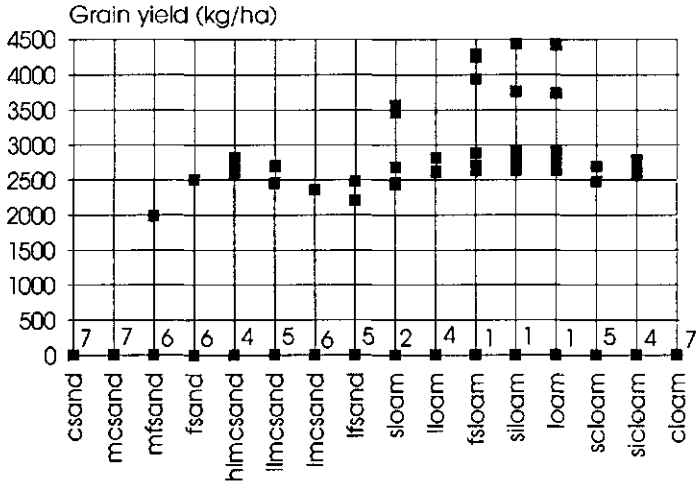

Figure 9. Predicted rainfed upland rice yield in the wet season (sowing date is day 150) on various soils, Patancheru, 1978 - 1984. The numbers on the X-axis indicate the numbers of aborted simulations due to severe drought stress (see text). The abbreviations of the soil types are: csand = coarse sand; mcsand = medium coarse sand; mfsand = medium fine sand; fsand = fine sand; hlmcsand = humous loamy medium course sand; llmcsand = light loamy; medium course sand; lmcsand = loamy medium coarse sand; lfsand = loamy fine sand; sloam = sandy loam; lloam = loess loam; fsloam = fine sandy loam; siloam = silt loam; loam = loam; scloam = sandy clay loam; sicloam = silt clay loam; cloam = clay loam.

during the growing period. It is noted in Figure 4 that, even with sowing dates early in the rainy season, predicted yields are sometimes 0 kg ha^{-1}. This is because the rainfall distribution is sometimes so erratic that severe drought stress occurs in the early vegetative phase of crop development. In ORYZA_W, the simulation of crop growth is stopped after more than three consecutive days of severe stress (see above), thus leading sometimes to 0 kg ha^{-1} predicted grain yield.

Upland rainfed rice yield in freely draining conditions is much affected by soil type. Soils of different texture have different water holding capacities, which is of crucial importance for the storage and availability of water for crop growth. Rice yield was predicted for 16 different soil types ranging from coarse sand to clay loams (Figure 9). Clay soils are generally not freely draining, and therefore not included in this analysis. In all simulations, the sowing date was day 150 (beginning of the rainy season). Sandy soils with low water holding capacity mostly had a severely stressed growth in all seven years of simulation (0 kg ha^{-1} predicted rice yield). The best (freely draining) soil types were loamy soils with no clay content, viz. sandy-, fine-sandy-, and silty-loam, light loam and 'true' loam. On these soils, predicted rice yield could reach values of 3.5 - 4.5 t ha^{-1} in good years.

The exceedance probability of upland rice yield with sowing dates between days 140 - 160 on loam, silty-loam and sandy-loam is given in Figure 10. The probability of severe

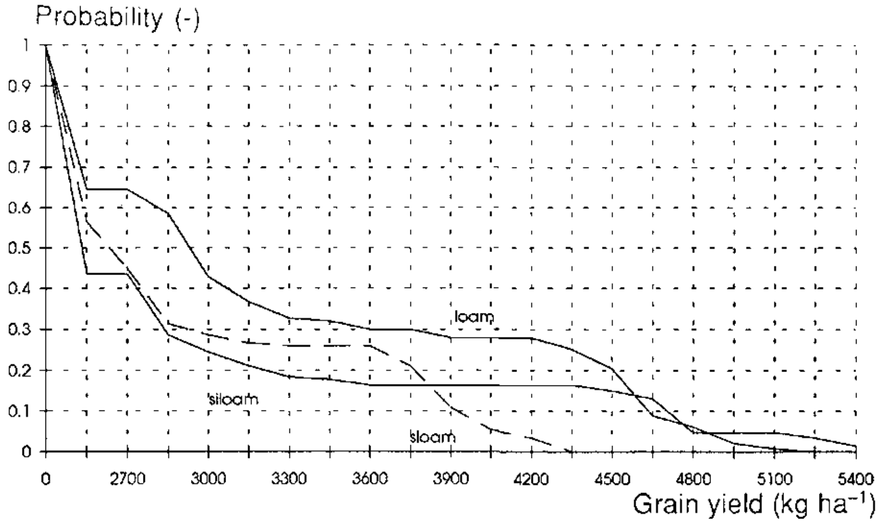

Figure 10. Exceedance probability of rainfed upland (rough) rice yield in the wet season (sowing date is between days 140 - 160) at Patancheru, 1978 - 1984, on loam, silty-loam (siloam) and sandy-loam (sloam).

drought stress (yield < 2.25 t ha^{-1}) was 35, 55 and 40% for loam, silty-loam and sandy loam, respectively. True loam soils had the highest probability of relatively high yields, followed by silty-loams and sandy-loams. The probability of realizing 4 t ha^{-1} or more was about 30% on loam, 15% on silty-loam and 10% only on sandy loam.

Next to soil type, rainfall was the most determining factor for crop growth. In Figure 11, predicted crop yield is plotted versus accumulated rainfall during the growing period for the crops of Figure 9. Linear equations were used to relate crop yield to accumulated rainfall:

True loam:	Yield	=	1041	+	3.67	× rainfall	(kg ha^{-1})	(1)
Silty loam:	Yield	=	733	+	4.12	× rainfall	(kg ha^{-1})	(2)
sandy loam:	Yield	=	1301	+	2.66	× rainfall	(kg ha^{-1})	(3)

On true loamy soils, accumulated rainfall accounted for 84% of the variation in predicted rice yield, on silty-loams for 80% and on sandy-loams for 84%. Relationships such as these can be used as first indicators of expected yield on the basis of accumulated rainfall.

Concluding remarks

The use of crop growth simulation modelling and systems analysis was demonstrated in the exploration of the effects of weather and soil on rice cropping. The effect of climate (radiation, rainfall, temperature) and soil characteristics (texture, seepage and percolation rates) on rice yield was quantified in irrigated lowland and rainfed upland environments, for

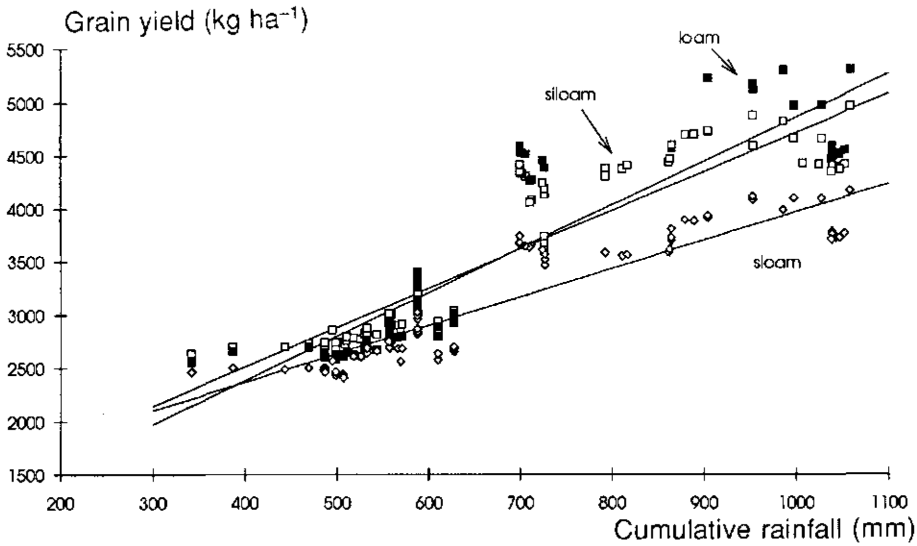

Figure 11. Rainfed upland rice yield in the wet season (sowing date is between days 140 - 160) versus accumulated rainfall during the growing period, Patancheru, 1978 - 1984. The soil types were loam, silty-loam (siloam) and sandy loam (sloam).

a case-study at Patancheru (Hyderabad, India). The results are useful in designing and optimizing cropping strategies and irrigation systems in relation to rice yield and irrigation requirements in different agro-ecosystems. It should be noted, however, that the case-study presented in this paper served as an illustrative example; though weather data were taken from a meteorological station on the site, crop and soil data were taken from literature and from field experiments conducted elsewhere. High potential yields with no sink limitation were predicted by using the IR72 crop data that were derived from IRRI experiments with very high N applications (up to 225 kg ha^{-1}). In actual studies, soil data should be taken from field observations or from soil maps from the area under study, and crop characteristics should be derived for locally used varieties (e.g. Palanisamy et al., 1993; Bouma et al., 1993). The growth model should be well validated under local conditions before it can be used to explore cropping and irrigation scenarios. In the SARP project, the agro-ecological rice growth model ORYZA_W is still under further development. The effects of drought stress in lowland environments is being elaborated from field experiments so that rainfed lowland environments can also be simulated (Wopereis, 1993). For this purpose, shrinkage and cracking of the puddled soil under drought stress have been studied and incorporated in the water balance model. Also, effects of low and high temperatures on spikelet fertility have yet to be included in the model.

For agro-ecological studies on regional scales, Geographic Information Systems (GIS) form a powerful tool for combination with simulation modelling (Aggarwal, 1993; Wopereis, 1993). Maps of soil and topographic data can be digitized and stored in raster or vector format. Point observations from meteorological stations and from field trials can be extrapolated to land units that can be overlaid with the soil and topographic digitized maps.

For each unique land unit (i.e. agro-ecological environment), simulation modelling will lead to indications of yield potential, irrigation requirements and optimum cropping system design.

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Application of model simulation to evaluate rice production at the district level

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Abstract

The production of rice in the north-east of Thailand is greatly determined by the amount and distribution of rainfall. Because of the erratic pattern of rainfall and the low soil water holding capacities, the production of rice is unstable. To deal with the complexity of the rainfed environmental conditions of this region, information technology has been adopted as a means to provide primary information for agro-ecological zonation and research planning. The present investigation is carried out to further refine the structure of the system prototype.

Rainfed rice production in 1991 of Phra Yun district, Khon Kaen, Thailand was analysed using the rice growth model MACROS. Precipitation in the study area was approximated according to the Thiessen method using four weather stations. Groundwater table depths were estimated by an empirically derived equation. The distribution of soils in the paddy areas was analysed by using GIS, and their properties were input for the crop model. MACROS was then applied to estimate rice yield for each soil series. The simulation results were used to classify the area into six agro-ecological production zones. The simulated yields for each zone were compared with actual values obtained from questionnaires to farmers. In general, simulated values were about twice as high as actual values, indicating a yield gap of roughly 2000 kg ha^{-1} between the actual yield level and obtainable yields under optimum nutrient supply and no pest/disease infestation.

Introduction

Agro-ecosystem analysis of the north-east of Thailand has indicated that the cultivated area can be classified into flood plain, non-flood plain, and mini watershed of undulating land (KKU-FORD, 1982). The first two zones are cultivated mainly with paddy (rice). Within the mini watershed, rice is grown in the depressions, and upland crops on the elevated land in between. Because of the topographic characteristics of the north-east, irrigation is limited to only 20% of the total cultivated area. Rice production is thus greatly determined by the amount and distribution of the rainfall. The variation of rainfall affects the production of rice in two manners. First, the amount and distribution preceding the transplanting determines the extend of actual planted area and the time of transplanting. Secondly, the amount and distribution of rainfall after transplanting determines the growth and final yield of the crop. Because of the erratic pattern of rainfall, coupled with a low water holding capacity and a low natural fertility of the soils, the production of rice in the north-east is very unstable, especially in the central and western parts of the region. Considerable efforts have been made to raise and stabilize rice yields through varietal improvement, suitable crop management, and improved cropping systems. However, success of the agro-technological transfer is restricted mostly to those areas which have similar environmental conditions to those of the experimental sites. To deal with the complexity of the rainfed environmental conditions of the north-east, information technology has been adopted as a tool to provide primary information for agro-ecological zonation as well as to analyse alternative systems of crop production. In previous studies, preliminary application of simulation modelling and Geographic Information Systems in the evaluation of rice production in the five subdistricts of Phra Yun district in north-east Thailand has confirmed their potential and capabilities. Positive correlations were obtained between simulated rice production and those reported by the Department of Agricultural Extension Office, Phra Yun district, Khon Kaen (Pannangpetch, 1991). The present investigation was thus carried out to further refine the structure of a prototype of the developed information system.

Material and methods

Study area

The analysis and evaluation of rice production was made for Phra Yun district, Khon Kaen, Thailand, during the wet season of 1991. Phra Yun district is located on 16° 20' latitude and 102° 40' longitude. The district has a total area of approximately 18478 ha, and is administratively divided into five subdistricts (Figure 1). Topographical, Phra Yun district is mainly a shallow undulating mini watershed which is representative for a large proportion of cultivated land of the central part of the north-east area of Thailand. Land elevation has indicated that the most promising areas for agriculture are located in the alluvial plains of the eastern and western parts of the district.

Crop model

The crop model MACROS with the modules L1D, L2C and L2SS (SAWAH water balance, see Penning de Vries et al., 1989) was used to simulate rice production under rainfed conditions for five subdistricts of Phra Yun district. The model was extended with a subroutine to estimate the depth of the groundwater table (SUZW) which is described in a section below, and the subroutine SUNBAL describing the distribution of Nitrogen within the crop (Pannangpetch, 1993). However, a modification was made to the subroutine SUNBAL such that the spontaneous processes of leaf senescence would begin only when the leaf weight of the crop is higher than 50 kg ha^{-1}. The modified model MACROS simulated crop growth under rainfed (water-limited) conditions, but with optimum nutrient supply (N is not limiting crop growth) and without any pest or disease occurrence.

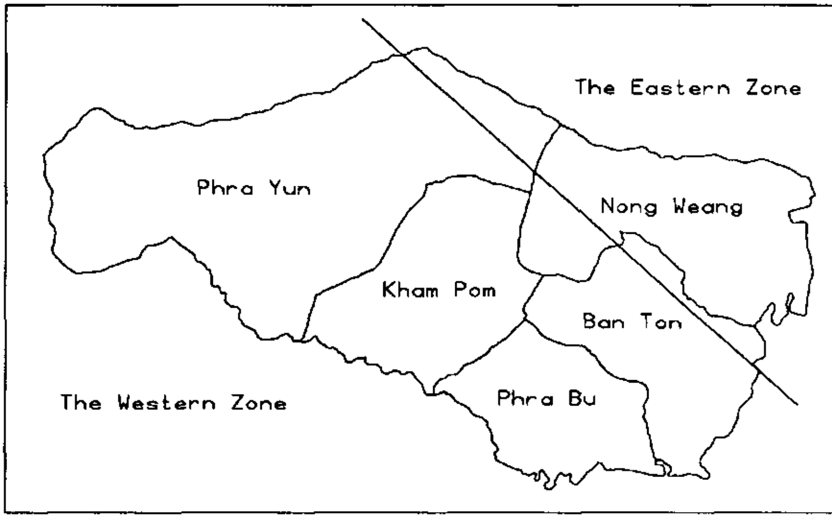

Figure 1. Phra Yun district and its subdivision into five subdistricts. The straight line separates the two precipitation zones as approximated by the Thiessen method.

Crop input parameters

Crop parameters derived from the variety RD6 (Pannangpetch et al., 1991) were used in the MACROS model.

Meteorological data

Daily precipitation of each subdistrict was estimated from four weather stations located around Phra Yun district (Khon Kaen, Ban Phai, Mancha Khiri and Phu Wiang) by the Thiessen polygon method. Because the distance between the four weather stations was much greater than the distance across the boundary of Phra Yun district, only the zones (polygons) belonging to the Mancha Khiri and to the Khon Kaen station fell within the district, the western zone and the eastern zone, respectively (Figure 1). Precipitation data of Khon Kaen University and Mancha Khiri weather stations are shown in Figure 2. All other meteorological input data that were needed in model simulation were obtained from the Khon Kaen University weather station: daily radiation, maximum and minimum temperature, air humidity and wind speed.

Distribution of soils

The geographic distribution of (paddy-)soils in the five subdistricts was identified by using a Geographic Information System. Maps of soil series and of paddy areas, and the boundaries of the five subdistricts were digitized from map sheets of DLD (1973) and RTSD (1986), respectively. The three digitized maps were overlaid to give polygons of

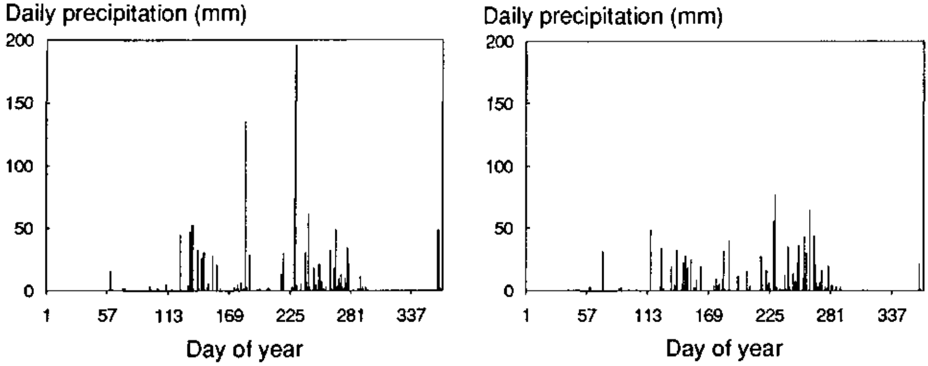

Figure 2. Daily precipitation in 1991 from Khon Kaen University weather station (left) and from Mancha Khiri weather station (right).

Table 1. Acreage (ha) of the 13 soil series in the paddy lands of the five subdistricts of Phra Yun district.

	Subdistricts of Phra Yun district					
Soil Series	Phra Yun	Kham Pom	Phra Bu	Ban Ton	Nong Weang	Tot. area
Alluvial plain						
Alluvial Complex	0	13	49	25	106	193
Phimai	0	0	76	103	0	179
Ratchaburi/Phimai	0	0	0	135	0	135
Ratchaburi	0	0	51	0	0	51
Low terrace						
Roi et	2143	803	724	489	652	4811
Roi et / high phase	101	211	101	22	274	709
Ubon	17	49	0	0	0	66
Middle and high terrace						
Korat	461	227	133	132	389	1342
Satuk	286	10	0	22	2	320
Phon Phisai	48	68	93	6	91	306
Korat/Phon Phisai	0	188	0	0	0	188
Yasothon	48	0	0	0	0	48
Nam Pong	1	0	0	0	0	1
Paddy area	3105	1569	1227	934	1514	8349
Total area	7389	2849	2051	2666	3523	18478

combinations of soil type, paddy land and administrative subdistrict. There were 13 soil series within the paddy land of Phra Yun district, predominated largely by the Roi-et (Re), and Korat (Kt) soil series. According to the association of soil series with the toposequence (Moormann et al., 1964), these 13 soil series were categorized into those of alluvial plains, low terraces, and middle and high terraces. The acreage of the 13 soil series in the paddy areas of the five sudistricts is presented in Table 1, and their spatial distribution is depicted in Figure 3. Information on the texture and profile of these soil series was derived from DLD (1973), and used as input for the module L2SS (SAWAH water balance) of the model MACROS.

Groundwater table

Presently, information on the depth of the groundwater table at various times during the year is not commonly available. As a consequence, a limitation is imposed on the extent that crop modelling can be applied to simulation and optimization of crop production under rain-fed conditions in the north-east of Thailand. To overcome this limitation, an attempt was made to construct an empirical equation to describe the rate of change in the depth of the ground water table as a function of daily precipitation and of the previous depth of the ground water table.

Visual observation suggested a similarity in the topographic characteristics of the Ban Kok Yai and the Phra Yun district. Therefore, measured daily precipitation and depths of the ground water table in lower and upper paddy fields at Ban Kok Yai in 1987 and 1988, were used to derive an empirical relationship that was supposed to be valid for the Phra Yun district too:

$$\Delta ZW = (VFLMX/ZWMX)\,(ZWMX - ZW) + \ldots$$
$$RAIN \bullet [(LFACMX/(ZWMX \bullet 0.5)^2\,) \bullet (ZWMX - ZW) \bullet (ZWMX) + 1] \quad (1a)$$

$$ZW_t = ZW_{t-1} + \Delta ZW \bullet \Delta t \quad (1b)$$

where

ZW is the depth of groundwater table (m),
ΔZW the rate of change of ZW (m d^{-1}),
ZWMX the maximum depth of ground water table (m),
RAIN the daily precipitation (m),
VFLMX a constant (m d^{-1}), and
LFACMX is a constant (-).

The depth of the groundwater table is relative to the top of the bund.

Using the above Equations 1a and b, the depth of the groundwater table in low and in middle terraces of Ban Kok Yai were estimated for 1987 and 1988, and compared with measured data (Figure 4). The height of the bund used in the estimation was 0.3 m. For the low terrace, the values obtained for ZWMX, VFLMX and LFACMX were 1.35 m, 0.045

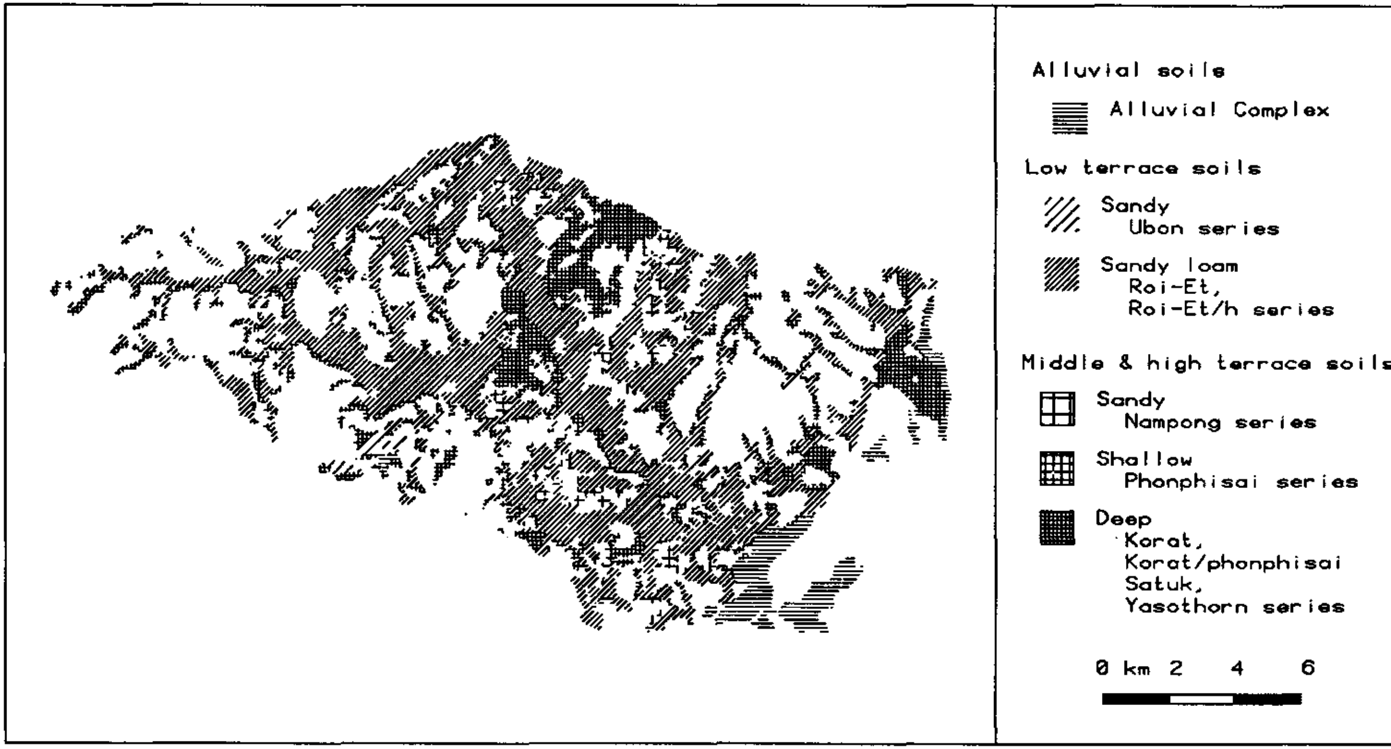

Figure 3. Soil groups in paddy of Phra Yun district.

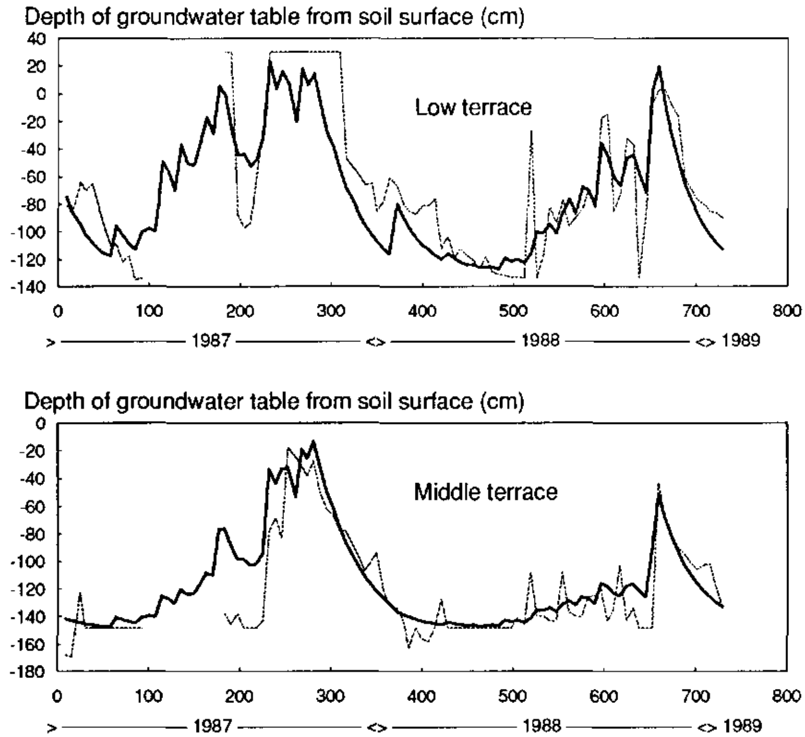

Figure 4. Measured depths (dashed line) and estimated depths (solid line) of the groundwater table in low terraces (top figure) and in middle terraces (bottom figure). A discontinuity in the dashed line indicates missing (measured) data.

m d^{-1} and 10.0 (-), respectively. The initial depth of the groundwater table (ZWI) was 0.7 m. For the middle terrace, the values for ZWMX, VFLMX, LFACMX, and ZWI were 1.5 m, 0.045 m d^{-1}, 5.5 (-) and 1.3 m, respectively. It should be noted that the values of the above constants were relative to the soil surface.

From the results of the comparison between estimated and measured data, it was concluded that the derived relationship adequately estimated the depth of the groundwater table. Eqns 1a and b were translated into a subroutine (SUZW) and used to substitute the arbitrary function ZWTB in the module L2SS, as described by Penning de Vries et al. (1989). The listing of the subroutine SUZW is shown in Table 2. The subroutine also included a switch variable (ZWSW). The value of ZWSW equals 1 when the water table is 2 cm above the soil surface for three consecutive days after daynumber 175; else ZWSW=0. When the water level is adequate for transplanting, simulation of crop growth is starts.

Simulation of crop growth

The growth and yield of rainfed rice was simulated for each soil series within each of the five subdistrict. Simulation began on the 1st of January 1991. In each case, simulation of

Table 2. Listing of the subroutine SUZW to calculate the depth of groundwater table from daily rainfall data.

```
DYNAMIC
   ZW, ZWSW = SUZW(DATE,TIME,RAIN,ZWMX,VFLMX,LFACMX,WL0MX,ZWI)
END
STOP
C     Subroutine to simulate ground water table.
      SUBROUTINE SUZW(DATE,TIME,RAIN,ZWMX,VFLMX,LFACMX,WL0MX,ZWI,
   $ ZW, ZWSW)
      IMPLICIT REAL(A-Z)
C     To initialize depth from the top of the bun
        IF (TIME .EQ. 0.0) THEN
          INDX=0.0
          ZWSW=0.0
          FZWMX=ZWMX+WL0MX
          K=LFACMX/((FZWMX/2.0)**2)
          FZW=ZWI+WL0MX
          ZW=ZWI
        ELSE
          FZW=FZW+ZWR
          ZW=AMAX1((FZW-WL0MX),(-WL0MX))
        ENDIF
C      To set the switch to begin transplanting after day 175 and
C      when surface water is above 2 cm for 3 consecutive days
        IF (ZWSW .LT. 1.0) THEN
            IF ((DATE .GT. 175.0) .AND. (ZW .LT. -0.02)) THEN
              COUNT=1.0
            ELSE
              COUNT=0.0
            ENDIF
        INDX=INDX*COUNT+COUNT
        ZWSW=AMAX1(0.0,INDX-2.0)
        ENDIF
        ERAIN=AMAX1(0.0,(RAIN-3.0))/1000.0
        VFLO=(VFLMX/FZWMX)*(FZWMX-FZW)
        LFAC=(K*FZW*(FZWMX-FZW))+1.0
        INFLO=ERAIN*LFAC
        ZWR= VFLO-INFLO
        RETURN
        END
ENDJOB
```

crop growth started only when the surface water in the paddy, as estimated by the subroutine SUZW, was higher than 2 cm above the soil surface for three consecutive days. The initial weight of leaves and stems was 25 and 50 kg ha^{-1}, respectively.

Questionnaire data for comparison with the simulation results

Questionnaires on the actual planted area and yield in 1991 were given to 190 selected farmers by the Department of Agricultural Extension Office, Phra Yun district, Khon Kaen. The selection of farmers was based on the location of the paddy fields so that information on rice production on each soil series in each subdistrict was obtained. With the permission from the Extension Office, the answers to these questionnaires were compiled to obtain data for comparison with the result from the simulation modelling.

Results and discussion

Simulated rice yield and dates of transplanting are given in Table 3. Transplanting could be done considerably earlier in the eastern part of the district than in the western part. This was caused by relatively high precipitation in May and June in the eastern district (note: on day 184 a precipitation peak of 135 mm was recorded by the Khon Kaen University weather station). Within each part of the district, transplanting could always begin earlier for the paddy in the lower terraces than in the upper terraces. After transplanting, the amount and distribution of rainfall was adequate to meet the demand by the crop on all soil series. Therefore, the differences in soil texture and soil profile between the soil series did not lead to differences is (simulated) crop growth and yield. On the basis of the simulation results, paddy land in the Phra Yun district can be grouped into six 'agro-ecological' zones; alluvial plains, low terraces, middle and high terraces of the eastern part, and middle and high terraces of the western part.

In general, simulated yield levels were twice as high as the yields obtained from the farmers questionnaires (Table 3). The gap between simulated and currently realized yields

Table 3. Simulated rice yield (kg ha^{-1}) and transplanting dates (day of year) grouped into six agro-ecological zones. For comparison, also the rice yields as obtained from the questionnaires are given.

Agro-ecological zone	Questionnaires	Simulation	
	Yield	Yield	Day of transplanting
Western part			
Alluvial plains	2005	4645	221
Low terraces	1917	4248	231
Middle and high terraces	1418	1703	264
Eastern part			
Alluvial plains	1702	4481	176
Low terraces	2056	4648	186
Middle and high terraces	1744	4143	232

indicates that there is scope for an improvement of about 2000 kg ha^{-1} in the rainfed rice production (techniques) in Phra Yun district. The model simulations were carried out for conditions of optimum nutrient supply and without pest and disease infestation. In practice, however, nutrient supply is not optimal, farmers do not always give high doses of fertilizer because of the risks of crop failure. Also, in practice, pests and diseases do occur in Phra Yun district. Another reason for the difference between simulated and realized rice yields may be caused by errors in the model simulations. For instance, the distance between the weather stations used in estimating the precipitation of each subdistrict may have been too long, resulting in large deviations between actual and estimated precipitation values. The functioning of the model itself has to be validated with (high-quality) measured input data on well-designed field experiments. Finally, a third source of difference between simulated and actually obtained rice yields might be the questionnaires themselves. For instance in the eastern part of Phra Yun, only 13 questionnaires were used for Nong Weang subdistrict. This number might be too low to give a reliable estimate of the subdistricts mean rice production.

Acknowledgement

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Case study on regional application of crop growth simulation models to predict rainfed rice yields: Tarlac province, Philippines

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Abstract

Paddy rice is the major crop grown during the monsoon season (June - November) in the Philippines. Under non-irrigated growing conditions, rice yield losses may occur due to drought. In this study, the potential of crop simulation models to quantify such risk on a regional level, based on soil hydrological and climatic data was investigated. For this purpose, soil hydraulic properties were determined for 7 major soil types under rice cropping occurring within the province of Tarlac in the Philippines. The crop growth model ORYZA1-DSTRESS-PADDY was used to predict rainfed rice yield as a function of these soil characteristics and long-term weather information (25 years). Potential (irrigated) rice yield varied from 5.4 to 6.7 t ha^{-1}. The impact of groundwater table depth on capillary rise and rainfed rice yield was investigated for each of the 7 major soil types. The importance of puddling intensity on water use efficiency and rice yield was studied by varying the saturated hydraulic conductivity of the least permeable layer in the puddled topsoil. Water-limited (rainfed) rice yield ranged from 0 to 6.7 t ha^{-1}. Risk involved in growing rainfed rice was quantified by calculating yield probability distributions for each soil type. Spatial variability of simulated rainfed rice yield within the province was analysed using a Geographic Information System.

Introduction

One of the major limitations to rice production in the Philippines is water supply and availability. A large part of the total Philippine rice production is from rainfed areas where rice is grown only once a year during the wet season (June - November). For the rest of the year these areas are usually left fallow. Erratic rainfall results in yield variability. In some areas, due to increasing urban and industrial demand for water, irrigation schemes can support only part of the area they were designed to service. In addition, poor management and eroding infrastructure contribute to unsatisfactory performance of irrigation systems (Bhuiyan, 1987), thus increasing the amount of rice grown under rainfed conditions.

In both, irrigated and rainfed rice areas there is a need to optimize water use efficiency at the regional level. This can be done through: (*i*) improvement of irrigation facilities, (*ii*) introduction of water-saving techniques, (*iii*) adjustment of choice of crop and/or planting time. For any of these approaches, a thorough systems analysis is needed to evaluate different solutions for different environments.

A systems analysis, in this case, can not rely on traditional agronomic field station or farmer's field experiments. This would be too costly and time consuming, given the need to conduct such experiments over a number of years, cropping seasons, and across different environmental conditions. Especially in rainfed environments, experiments must be conducted over a large number of years, to allow for climatic variability.

To overcome such limitations, crop growth simulation models can be used to determine potential (fully irrigated) and water-limited (rainfed) yields for a target area, provided adequate data on soil, weather and crop and soil management procedures are available. Efforts are currently underway to evaluate different cropping systems in centuries old tank irrigation systems in Tamil Nadu, South India, using simulation models to minimize risk of crop failure. Poor maintenance of these tank irrigation systems cause declining command areas and reduced rice yields due to water scarcity in November - December, at the end of the growing season (Palanisami, 1993). The potential of water-saving techniques in different environments, like puddling (Wopereis et al., 1992a, b), or the introduction of a pre-tillage before re-flooding a dry cracked field for the next rice crop (Wopereis et al., 1993b) are best evaluated using simulation models as well, provided long-term weather data and reliable soil data are available.

An economic evaluation of strategies to optimize water use efficiency requires an accurate estimate of the probability distribution of production (Anderson, 1991). Simulation models can provide such probability distributions using long-term weather data. For a spatial analysis of drought risk, models need to be linked with a Geographic Information System (GIS) containing soil and long-term weather data of the target area (Nix, 1987).

In this study, the potential of crop simulation models to quantify drought risk in rainfed rice environments based on soil hydrological and climatic data was investigated. A methodology is presented to obtain soil hydraulic input data on a regional scale. A case study was conducted for a province in central Luzon, one of the major Philippine islands.

Material and methods

Simulation models should be validated for environmental conditions prevailing in their target area. Recently, Kropff et al. (1993) introduced ORYZA1, an improved model for irrigated rice production. The model was validated with a large number of field experiments, and yields can be predicted accurately for a range of environments. Input requirements for yield prediction using the model ORYZA1 are:

- Geographical latitude,
- Plant density,
- Date of crop emergence and transplanting, and
- Daily weather data (radiation, temperature).

In rainfed rice environments, the model ORYZA1 needs to be coupled to a soil-water balance via an 'interface' that translates the soil-water status in a crop response.

For this study, a soil-water balance module (PADDY) was developed that can be used for puddled soils. Greenhouse studies were conducted to investigate the impact of temporary drought, induced at different growth stages, on rice growth and yield. This experimental work resulted in a 'drought stress' module (DSTRESS). DSTRESS translates the soil moisture status predicted by PADDY in a crop response predicted by ORYZA1. The soil and crop components of the combined ORYZA1-DSTRESS-PADDY model were validated using field experimental data (Wopereis, 1993).

In addition to the data needs of ORYZA1 specified above, use of the ORYZA1-DSTRESS-PADDY model requires:

- Daily weather data (wind speed, relative humidity, rainfall),
- Soil hydraulic properties (i.e. hydraulic conductivity and water retention characteristics and saturated moisture content of the puddled topsoil), and
- Daily data on groundwater table depth.

Study area

The province of Tarlac is located in the northern part of the Philippines on the island Luzon (Figure 1). The province covers an area of approximately 300,000 ha. It is composed of 17 municipalities with a total population of about 740,000 people (BSWM, 1992).

Three major landscapes can be identified in the province: an alluvial floodplain in the north-east, a hilly area in the centre of the province and a mountainous area in the west (Figure 2). The alluvial floodplain occupies about one third of the province area and is dissected by rivers and creeks. The hilly landscape is slightly undulating to strongly rolling terrain and is mainly composed of shale and sandstone. The mountainous landscape is of volcanic origin and is highly dissected with steep to very steep ridges. Pyroclastic hills border the province in the south. Due to the 1991 eruption of Mt. Pinatubo, part of this area is again covered with a thick layer of 'lahar', i.e. mud flow.

Crop and soil management

The area used for crop production in Tarlac is about 140,000 ha, and is mainly situated in the alluvial floodplain. The five major crops grown are rice (111,000 ha), sugarcane (20,500 ha), sweet potato (5,000 ha), corn (1,500 ha) and vegetables (500 ha). Of the area used for rice, 59,000 ha is irrigated, and 52,000 ha is rainfed (BSWM, 1992). Areas with adequate irrigation can be harvested twice a year; areas without irrigation can be harvested only once. Sugarcane and vegetable crops are grown on loamy to sandy soils.

Farmers use the first monsoon rains in May for rainfall collection. Soils are plowed and harrowed under near water saturated conditions using animal power or small hand tractors.

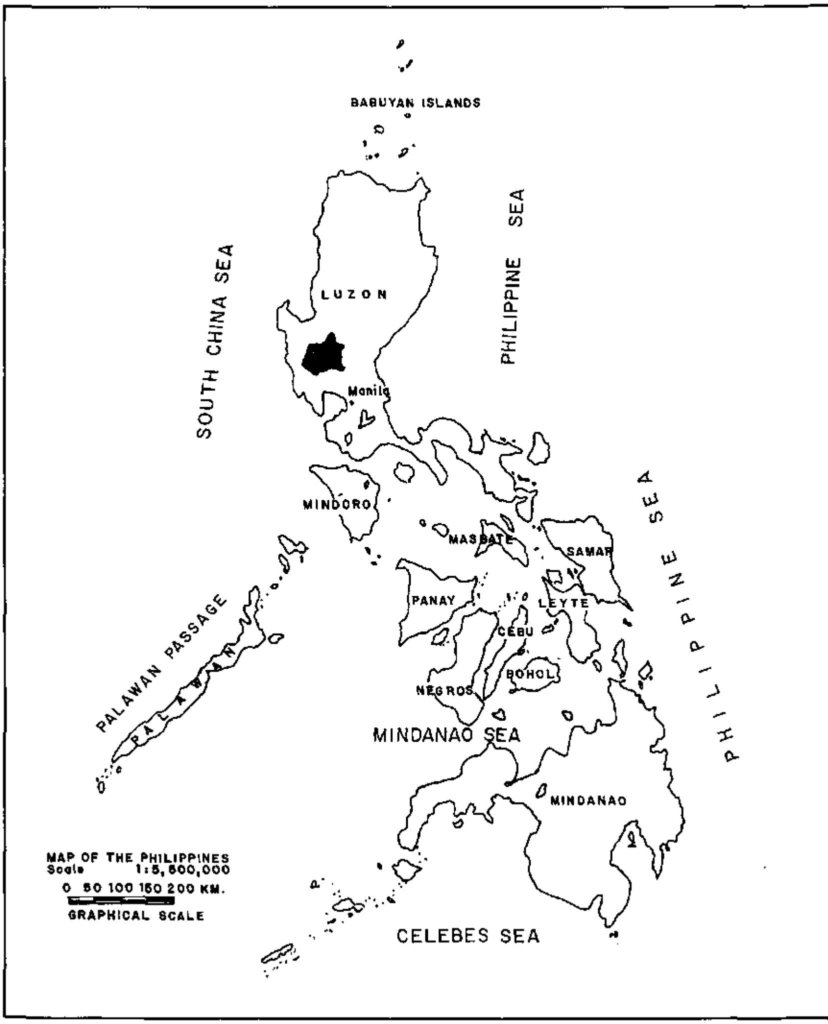

Figure 1. Location of the province of Tarlac in the Philippines.

Land preparation may require over one-third of the total water used for irrigated rice production (IRRI, 1978). Rice is usually transplanted between 15 and 30 June, although direct seeding is also practiced. Harvesting is normally done in October. In case of adequate irrigation facilities a second crop may be grown from November to April.

The average size of a rice farm in Tarlac is 1.7 ha. Farmers mainly apply inorganic fertilizer, often in two splits: one 7 - 30 days after transplanting and one around panicle initiation. Basal application is seldom used. Weed control measures are especially needed under rainfed conditions (BSWM, 1992).

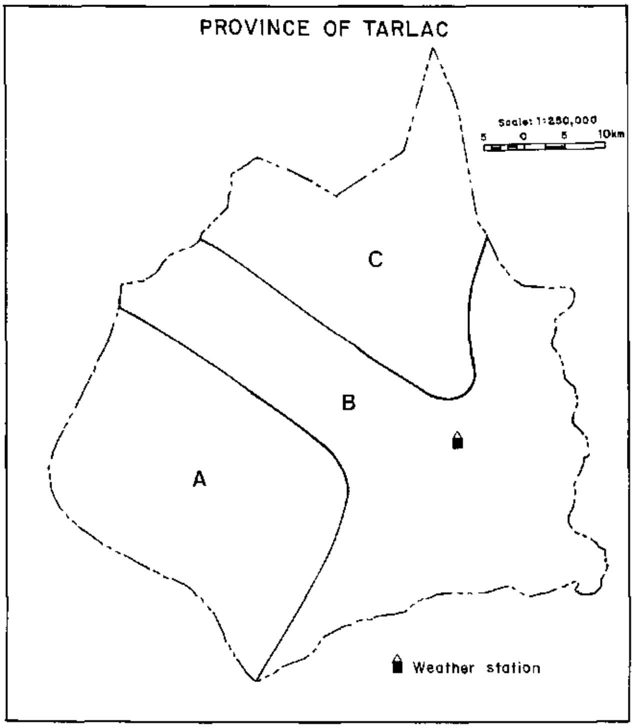

Figure 2. Location of major landscapes and weather station Hacienda Luisita in the province of Tarlac. A: High altitude volcanic mountains (above 500 m) and andesitic hills (2200 - 2900 mm rain yr^{-1}); B: Low altitude areas which are andesitic hills, terraces, footslopes and alluvial plains (1700 - 200 mm rain yr^{-1}); C: Alluvial plains (1300 - 1700 rain yr^{-1}). Source: BSWM, 1992.

Climate data

The province has two pronounced seasons: wet during June to November and dry from December to May. Most precipitation is due to monsoon rains that reach Luzon from the south west and west. There is only one fully equipped agro-meteorological station in the province, Hacienda Luisita (Figure 2). At the time of this study only five years of complete daily weather data were available from this station. This included daily observations of rainfall, relative humidity, maximum and minimum temperature and sunshine hours.

Highest maximum temperatures in Tarlac occur in April (36 °C). Lowest minimum temperatures are reached in January (19 °C). Rainfall is highest in the mountainous range with annual rainfall varying between 2200 and 2900 mm yr^{-1}. The alluvial plains receive about 1700 - 2200 mm yr^{-1} (BSWM, 1992; Figure 2). Because of the paucity of weather data, additional data on rainfall were obtained from the Philippine weather bureau PAGASA for 12 rainfall stations within the province. Although for some stations rainfall data were available for a large number of years, measurement series overlapped during only three

Table 1. Total solar radiation (averaged over three years) in the monsoon season for Hacienda Luisita and three of the nearest agro-meteorological stations, outside Tarlac province.

Station	Years	Total solar radiation ($MJ\ m^{-2}$)
Dagupan	1978-1980	2518
Cabanatuan	1978-1980	2652
Manila	1978-1980	2582
Hacienda Luisita	1978-1980	2555

years for 10 out of the 12 stations. No conclusions on geographical distribution of rainfall could be derived from these data.

Total solar radiation in the monsoon season (June - November) for Hacienda Luisita was compared with four agro-meteorological stations outside Tarlac. Again, only three years within each time series of measurements overlapped for all stations. Total solar radiation was quite similar for all four stations (Table 1).

The set of five years of complete daily weather data was considered insufficient to get an idea of yield variability within the province. The weather generator program SIMWTH (Supit, 1986) was, therefore, used to generate 25 years of weather from the available 5 years.

Soil survey data

A soil map of Tarlac province (1:50,000) was provided by the Bureau of Soils and Water Management, Quezon City, Philippines. The map contains 67 different mapping units. Each of these mapping units is characterized by a representative profile description and by laboratory data like texture and organic matter content for every soil horizon, distinguished within the profile. The detailed soil map was digitized using the GIS package PC-ARC/INFO (ESRI, 1987).

The total number of mapping units was reduced by generalization, taking into account similarity in soil properties and importance of the unit in terms of surface area. Soil mapping units belonging to the same soil series, were merged, which reduced the original number of mapping units from 67 to 25. Soil units that occupied less than 1% of the total province were merged with other similar units. A representative profile was selected for every generalized mapping unit, except for the mountainous area. This simplification of the original soil map was done by an experienced soil surveyor with a good knowledge of the diversity of soils in the Tarlac province.

Guided by the detailed soil map, representative soil profiles were located for each of the generalized soil units. Soil horizons within each of these representative profiles were grouped into hydraulic-functional horizons according to texture and a simple depth criterion (topsoil or subsoil). A similar approach was followed in Wopereis et al. (1993a).

Soil physical data

Sampling activities for the measurement of the soil hydraulic functions (i.e. water retention and hydraulic conductivity) were concentrated on hydraulic-functional horizons in every representative profile. Sampling was carried out in the dry season of 1991 (two replicate samples per hydraulic-functional horizon).

Procedures used for estimating the water retention curve relating soil water content θ to soil water pressure h were:

1 The hanging water column method (Richards, 1965) for -15 kPa $< h < 0$ kPa using 71 mm diameter, 70 mm height undisturbed cores, and
2 the pressure cell method (Klute, 1986) for $h < -100$ kPa, using 51 mm diameter, 20 mm height disturbed cores.

The saturated and unsaturated hydraulic conductivity k was measured as a function of soil water pressure h using a combination of three methods:

1 The constant head method of Klute (1986) for vertical saturated conductivity (k_s) using 0.25 m high and 0.2 m diameter soil cores
2 The crust method (Booltink et al., 1991) for -2 kPa $< h < 0$ kPa, using the soil samples of Method 1; and
3 The one-step outflow method (Kool et al., 1985) using 70 mm high and 70 mm diameter soil cores for -50 kPa$< h < 3$ kPa. Saturated samples were subjected to a pressure of 50 kPa, after equilibrium at a pressure of 3 kPa was reached (Booltink, unpubl. data).

Soil-hydraulic properties were assumed to be represented by van Genuchten's closed-form equation (van Genuchten, 1980) involving four unknown parameters: coefficients a, n, l and residual moisture content θ_r. Two other parameters, i.e. the saturated moisture content (θ_s) and the saturated hydraulic conductivity (k_s) where set equal to their measured values. Values for the four unknown parameters were determined by nonlinear least-squares fitting using the program MULSTP (van Dam et al., 1990) of measured time series of cumulative outflow and measured water-retention data. Crust method data were used to validate the fitted hydraulic conductivity curve soil-water pressures near saturation.

For three heavy clay soils an alternative way to determine the conductivity curve $k(h)$ was needed because of very low outflow volumes (< 5 ml) from the one-step outflow experiments. For these sites, $k(h)$ characteristics were derived using the Wind method (Wind, 1968) and 80 mm high, 100 mm diameter undisturbed cores. Experimental data were analysed using the WIND program (Halbertsma, unpublished) and parameterized in terms of van Genuchten's unsaturated functions using the RETC program (van Genuchten et al., 1991). In total, hydraulic conductivity and water-retention characteristics were determined for 30 hydraulic-functional soil horizons.

To mimic puddled soil conditions, the top 10 cm of large 0.25 cm height and 0.2 m diameter undisturbed soil cores were hand stirred during one minute in the laboratory using large quantities of water. Saturated volumetric moisture content of the puddled soil material was determined after one week (to allow for settling of the soil particles) using 100 cc cores. The hydraulic conductivity of the least permeable layer in the puddled topsoil was determined for two samples per soil type using the method outlined by Wopereis et al. (1992a).

Simulation of rice production

As a first qualitative step, soils unsuitable for rice growth were eliminated from the analysis. This included the mountainous area and light-textured soils, except for soils that were classified on the soil map as 'severely flooded' because of their proximity to a river. It was assumed that rice grown on such soils does not suffer from drought stress. Simulations were only conducted for potentially suitable soils.

Potential (irrigated) rice yield was simulated using the model ORYZA1. Water-limited (rainfed) rice yield was simulated using the model ORYZA1-DSTRESS-PADDY. Crop parameters for rice cultivar IR72 were derived from a wet season experiment conducted at IRRI in 1991 (Kropff et al., 1993). Simulations started at transplanting, assuming 30 days old seedlings. Initial LAI, temperature sum and development stage of the seedlings were taken from the study presented in Wopereis (1993). Initial rooting depth was assumed to be 0.05 m.

After discussion with an expert from the Bureau of Soils and Water Management, Quezon City, Philippines (Sanidad, pers. comm.), transplanting of rice was assumed to start when cumulative rainfall exceeded 75 mm during seven consecutive days after 1 June.

Thickness of the puddled topsoil was set to 0.2 m, with the least permeable layer occurring between 0.15 and 0.20 m depth. At transplanting, the puddled topsoil was assumed to be saturated with an initial ponded water depth of 0.05 m. Subsoil horizons were assumed to be at field capacity level ($h = -10$ kPa). Measured hydraulic conductivity functions for each soil horizon were input in the model.

The impact of groundwater table depth and thoroughness of puddling on rainfed rice yield was investigated for each of the major soil types under rice cropping. Groundwater table depth was varied between 0.5 and 1.0 m.

Wopereis et al. (1992a) determined the saturated hydraulic conductivity of the least permeable layer in the top 0.25 m of a puddled clay soil at the experimental farm of the International Rice Research Institute in the Philippines. Average value was 0.036 cm d^{-1} with 95% confidence limits at 0.027 and 0.045 cm d^{-1}. In this study, two classes of puddling (poorly puddled and well puddled) were considered and expressed in terms of the hydraulic conductivity k_s of the puddled topsoil:

well puddled: k_s (least permeable layer) = 0.01 cm d^{-1}

poorly puddled: k_s (least permeable layer) = 0.10 cm d^{-1}

Combined with the two groundwater table depths, four simulation series were created:

Series 1: k_s puddled topsoil = 0.01 cm d^{-1}; groundwater table depth = 0.5 m
Series 2: k_s puddled topsoil = 0.01 cm d^{-1}; groundwater table depth = 1.0 m
Series 3: k_s puddled topsoil = 0.10 cm d^{-1}; groundwater table depth = 0.5 m
Series 4: k_s puddled topsoil = 0.10 cm d^{-1}; groundwater table depth = 1.0 m

The approach outlined above can only result in a broad overview of yield losses due to drought in Tarlac. Soil types were characterized by measurements conducted at one representative site only. Spatial variability of soil hydraulic properties or depth to soil horizons is not taken into account. Sensitivity analyses can be conducted to investigate the importance of variability in model input parameters.

Validation

Simulated rice yields were compared with data reported by the Philippine Bureau of Soils and Water Management obtained during a survey in Tarlac in 1990. Some of the representative sites were revisited during the wet season of 1991 and sampled for grain yield. Most of these fields had received additional irrigation during the growing season, often through small gasoline driven pumps. An estimate of grain yield at the various sites was obtained by counting the number of hills in one m^2 and by determining grain yield for twelve hills. Six additional hills were analysed for N-content in stem, leaves and grains.

Table 2. Major soil types occurring in Tarlac province and relative surface area.

Code	Soil series	Surface area (%)
10*	Rugao clay loam	3.9
12*	Alaminos clay loam	2.9
18*	Padapada clay	5.6
25*	San Manuel silt loam	5.0
26*	Moncada clay loam	4.3
27, 28	Lapaz, Banga, Pawing loamy sand	4.3
30*	Zaragosa clay loam	12.0
46[1]	Barang, Cabetican, Quingua silt loam	3.7
52	Ramos, Luisita, Angeles, silt loam	7.1
59*	Tarlac clay loam	4.7
-	Villar fine sandy loam (hilly area)	5.2
-	Mountainous are, miscellaneous	41.3

* Soils under rice cropping.

[1] Soil series is mostly covered by mud flow (lahar) due to the 1991 Mt. Pinatubo eruption.

Results and discussion

Soil data

The digitized, generalized soil map of the Tarlac province is shown in Figure 3. The total number of mapping units was reduced from 67 to 14. Excluding the mountainous areas, 11 mapping units could be distinguished (Table 2). Generalization reduced the number of delineated areas (polygons) from 369 to 219. Van Genuchten parameters, determined for the representative profiles are listed in Table 3. Saturated moisture content and hydraulic conductivity refer to soil conditions prevailing in the dry season. Puddled volumetric soil moisture content for each soil type under rice cropping was in general 0.1 to 0.2 cm^3 cm^{-3} higher than the values indicated in Table 3.

Soil series 27, 28, and 52 (Tables 2 and 3) were considered unsuitable for rice growth because of their light texture. No simulations were conducted for soil series 46 as this soil type only occurs in the area devastated by the Mt. Pinatubo eruption.

Simulation results

Potential yields in the province varied from 5.4 to 6.7 t ha^{-1}. These yields are considerably higher than irrigated rice yields reported by BSWM (1992), which varied between 2.5 and 3.5 t ha^{-1}. This discrepancy may be due to a large number of factors, e.g. lack of fertilizer, incidence of pest and diseases etc., which are not taken into account by the model ORYZA1-DSTRESS-PADDY. Harvest data from the survey conducted for this study show much higher yields, which are more in agreement with model predictions (Table 4), which may be attributed to the fact that most farmers included in the survey used shallow gasoline-driven irrigation pumps to overcome dry spells.

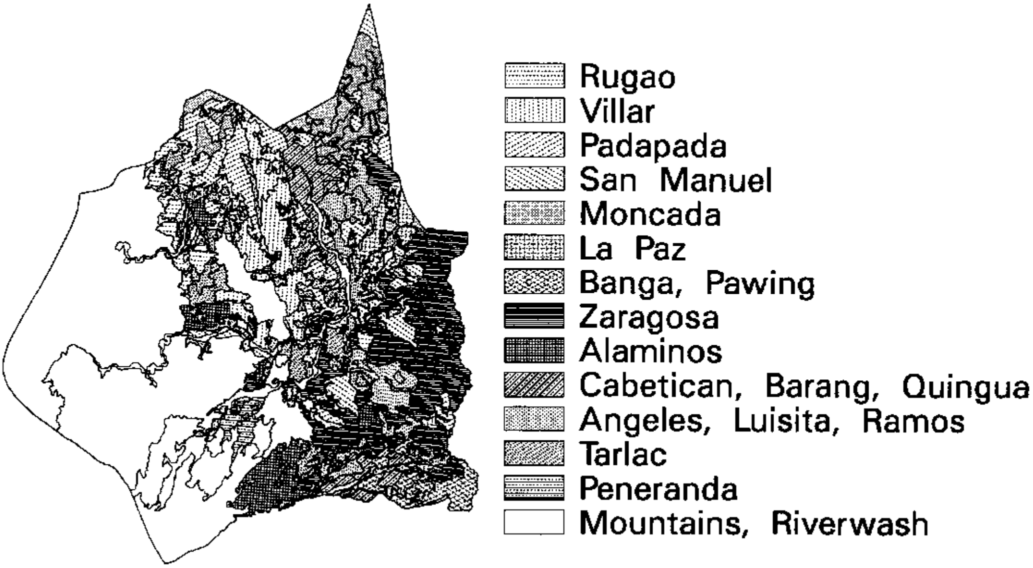

Figure 3. Generalized soil map of Tarlac province.

Table 3. Textural properties and van Genuchten's soil hydraulic parameters as estimated for hydraulic-functional horizons (code 1, 2, 3) occurring in representative profiles (e.g. code 25) of the Tarlac province.

Hor. code	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	k_s (m d^{-1})	θ_s (-)	α (cm^{-1})	n (-)	λ (-)	θ_r (-)
10-1	0-19	27.0	28.0	45.0	0.092	0.52	0.0171	1.114	–6.95	0.001
10-2	19-46	54.5	13.5	32.0	0.038	0.44	0.0176	1.261	0.15	0.001
10-3	>46	63.0	13.0	24.0	0.002	0.50	0.0009	1.397	5.77	0.001
12-1	0-16	33.0	24.0	43.0	0.41	0.65	0.0074	1.098	14.22	0.001
12-2	>16	24.0	27.7	48.3	0.02	0.49	0.0251	1.106	8.13	0.001
18-1	0-29	23.0	23.0	54.0	0.02	0.55	0.0036	1.233	–5.86	0.001
18-2	>29	19.0	17.5	63.5	0.015	0.57	0.0027	1.210	–5.17	0.001
25-1	0-23	2.4	43.2	54.4	0.05	0.44	0.0124	1.150	–4.96	0.005
25-2	>23	48.6	18.4	33.0	0.91	0.41	0.0283	1.175	18.89	0.193
26-1	0-31	9.4	26.6	64.0	0.03	0.45	0.0155	1.148	8.97	0.060
26-2	31-90	15.6	47.9	36.5	0.041	0.47	0.0031	1.256	29.82	0.004
26-3	>90	1.4	33.6	65.0	0.005	0.47	0.0034	1.235	–0.47	0.155
27-1	0-27	54.6	26.4	19.0	1.16	0.47	0.0097	1.618	3.34	0.044
27-2	27-58	81.6	6.4	12.0	5.43	0.48	0.0096	2.035	1.40	0.047
27-3	>58	86.8	3.7	9.5	6.20	0.48	0.0082	1.904	4.39	0.014
28-1	0-23	82.6	6.4	11.0	0.32	0.50	0.0056	1.639	5.04	0.028
28-2	>23	89.6	0.4	10.0	5.77	0.40	0.0133	2.963	1.82	0.052
30-1	0-17	36.0	37.0	27.0	0.07	0.47	0.0088	1.128	–1.91	0.011
30-2	17-32	34.0	27.0	39.0	0.21	0.46	0.0091	1.082	13.14	0.031
30-3	> 32	32.5	25.0	42.5	0.09	0.52	0.0121	1.122	31.98	0.001
46-1	0-29	33.2	41.0	25.8	0.08	0.43	0.0154	1.286	12.07	0.001
46-2	> 29	38.8	29.5	31.7	0.14	0.46	0.0116	1.145	6.80	0.133
52-1	0-22	69.0	16.0	15.0	0.18	0.43	0.0165	1.293	–0.93	0.001
52-2	22-82	80.0	4.5	15.5	1.08	0.41	0.0654	1.175	–1.15	0.071
52-3	>82	87.5	1.0	11.5	2.46	0.46	0.0317	1.434	7.07	0.105
59-1	0-18	74.4	2.6	23.0	0.05	0.49	0.0088	1.205	11.57	0.001
59-2	18-39	40.0	20.6	39.0	0.44	0.44	0.0204	1.107	17.57	0.001
59-3	>39	10.4	20.6	69.0	0.009	0.44	0.0630	1.120	–2.69	0.156

Table 4. Percentage filled grains, grain yield, plant density and N-content in stem, leaves and grains for several representative sites in the Tarlac province. (I = irrigated, R = rainfed; at site 28, two varieties were sampled: 28A = IR64 and 28B = IR72).

Profile Code	I/R	Filled grains (%)	Grain yield (t ha^{-1})	Plant density (hills m^{-2})	N-content Stem (%)	Leaf (%)	Grains (%)
10A	I	81.0	5.0	34	0.42	0.86	0.95
10B	R	63.2	3.0	27	0.44	0.95	1.17
18	I	73.7	4.2	40	0.37	0.42	0.99
25	I	66.8	4.5	35	0.56	1.51	1.25
26	R	57.1	1.7	35	0.63	0.28	1.27
27	I	89.0	4.6	27	0.29	0.49	0.91
28A	I	83.7	3.6	20	0.32	0.75	0.82
28B	I	78.7	5.3	20	0.44	0.87	0.95
30	I	72.0	6.6	46	0.41	0.60	1.07
52	I	81.3	4.9	38	0.55	0.68	1.04

Table 5. Average rainfed rice yields (t ha^{-1}) per soil type (see Table 2), calculated for Scenarios 1 - 4 (see text).

Soil type	Sc 1	Sc 2	Sc 3	Sc 4
10	5.3	5.2	4.1	3.8
12	4.6	4.6	2.8	2.8
18	5.3	5.3	4.3	4.3
25	5.5	5.3	4.2	3.7
26	4.9	4.8	3.8	3.8
30	4.7	4.4	3.5	3.1
59	5.5	5.4	4.2	3.9

Simulated rainfed rice yields for all soil types and simulation series are given in Table 5. For reasons of brevity, the variability of rainfed rice yield over 25 years for the four simulation series is shown in Figures 4 and 5 for two distinctly different soil types only (Zaragoza soil series and Padapada soil series). For comparison potential yields are also shown. From the graphs it follows that without additional irrigation facilities, growing rice under rainfed conditions is risky.

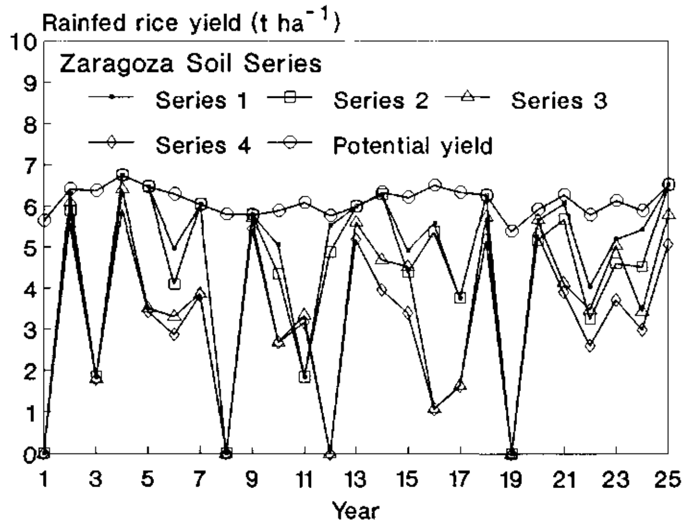

Figure 4. Potential and rainfed rice yield calculated for 25 consecutive wet seasons and four simulation scenarios on Zaragoza soil.

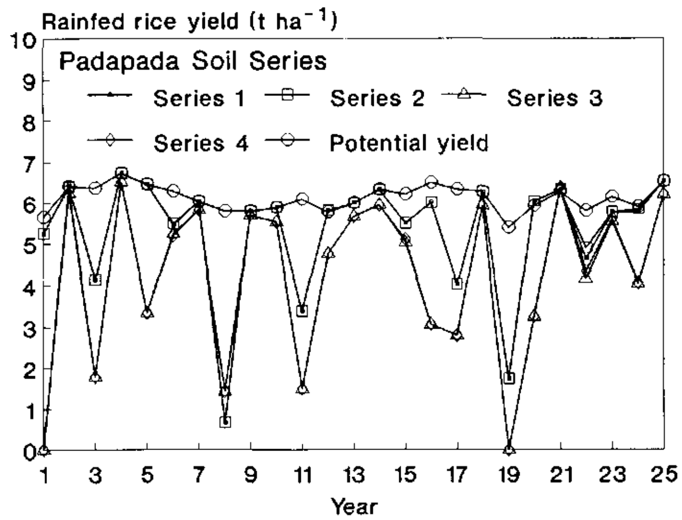

Figure 5. Potential and rainfed rice yield calculated for 25 consecutive wet seasons and four simulation scenarios on Padapada soil.

Comparison of rainfed yield with potential yields quantifies the yield gap between fully irrigated and rainfed production. This information indicates the yield losses farmers experience due to lack of irrigation water, under otherwise optimal growing conditions. Production risk was quantified by calculating cumulative probability functions for rainfed rice yield for each soil type. Results are shown for Zaragoza and Padapada in Figures 6 and 7. For Zaragoza, a shallow groundwater table had a positive effect on grain yield due to

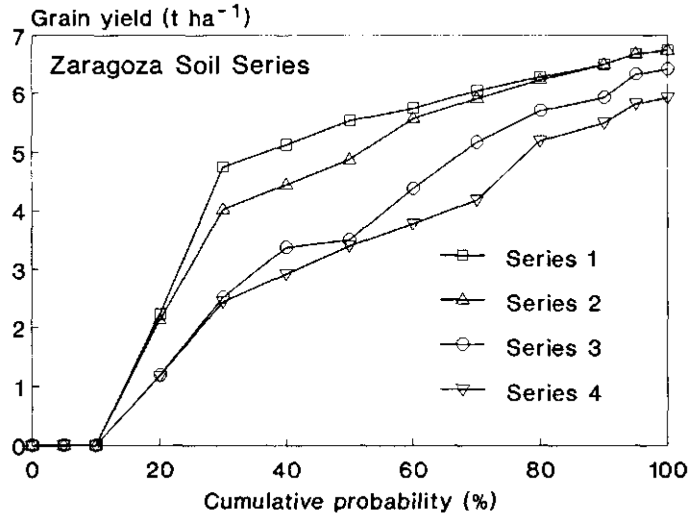

Figure 6. Cumulative distribution function for rainfed rice yield on Zaragoza soil.

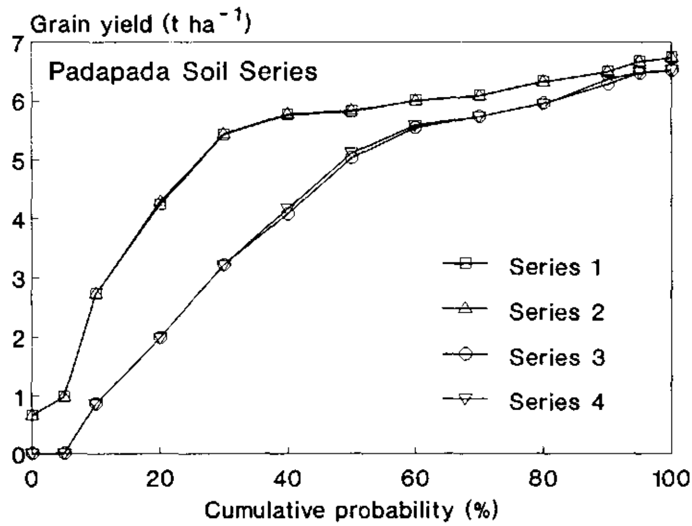

Figure 7. Cumulative distribution function for rainfed rice yield on Padapada soil.

increased capillary rise to the root zone. For Padapada this effect was almost non-existent. Poorly puddling resulted in yield losses for both soils, but yield losses were especially high for Zaragoza. These results can be attributed to the relatively permeable subsoil of Zaragoza soil series compared with the Padapada soil series, which makes the hydraulic resistance of the puddled topsoil less effective. If cracks penetrate through the puddled topsoil, water distribution within the soil profile as simulated by the PADDY water balance module, is determined by the hydraulic conductivity of the subsoil (Wopereis, 1993). For Padapada, water may start ponding on the soil surface even if deep cracks are present due to the low hydraulic conductivity of the non-puddled subsoil. For Zaragoza, a substantial amount of

Table 6. Hydraulic conductivity of the least permeable layer in the puddled topsoil (k_s) determined for the major soil types under rice cropping in Tarlac province. Measurements were conducted in the laboratory on two samples per soil series.

Soil type	Sample 1 k_s (cm d^{-1})	Sample 2 k_s (cm d^{-1})
10	0.09	0.161
12	0.015	0.025
18	0.014	0.0036
25	0.096	0.464
26	0.045	0.069
30	0.074	0.123
55	0.075	0.044
59	0.049	0.167

rainfall may be lost due to deep drainage if cracks have penetrated through the least permeable layer in the puddled topsoil.

The saturated hydraulic conductivity of the least permeable layer in the puddled topsoil of the Padapada clay determined in the laboratory, was about 0.01 cm d^{-1}, compared with 0.1 cm d^{-1} for Zaragoza clay loam (Table 6). Scenarios 1 and 2 seem therefore appropriate for Padapada, whereas scenarios 3 and 4 are more applicable to Zaragoza. This means that yield differences between Padapada and Zaragoza under rainfed conditions without any additional irrigation are large (Table 5).

The spatial distribution of risk due to temporary drought in the monsoon season in Tarlac can be mapped by assigning yield levels at different risk levels using a GIS. In this study, only one weather station was used, and a yield map therefore follows the boundaries delineated on the soil map.

Simulated rainfed rice yield was mapped at the 10 and 90% cumulative probability levels (Figure 8). Simulations were conducted assuming average k_s values determined in the laboratory (Table 6) and a groundwater table depth of 1.0 m. The Zaragoza soil series occupies a large part of the province (Figure 3, Table 2) and growing rice under rainfed conditions in the province is, therefore, risky.

For all soil types more effective puddling increased grain yields. Puddling may however create a zone of large resistance to root penetration at greater depth in the soil profile (plow pan). If this zone impedes exploration of the water reserves in the subsoil by the rice roots, puddling may have adverse effects on yield. This aspect was not investigated because of lack of good data on penetration resistance of the various soil types and its effect on root growth.

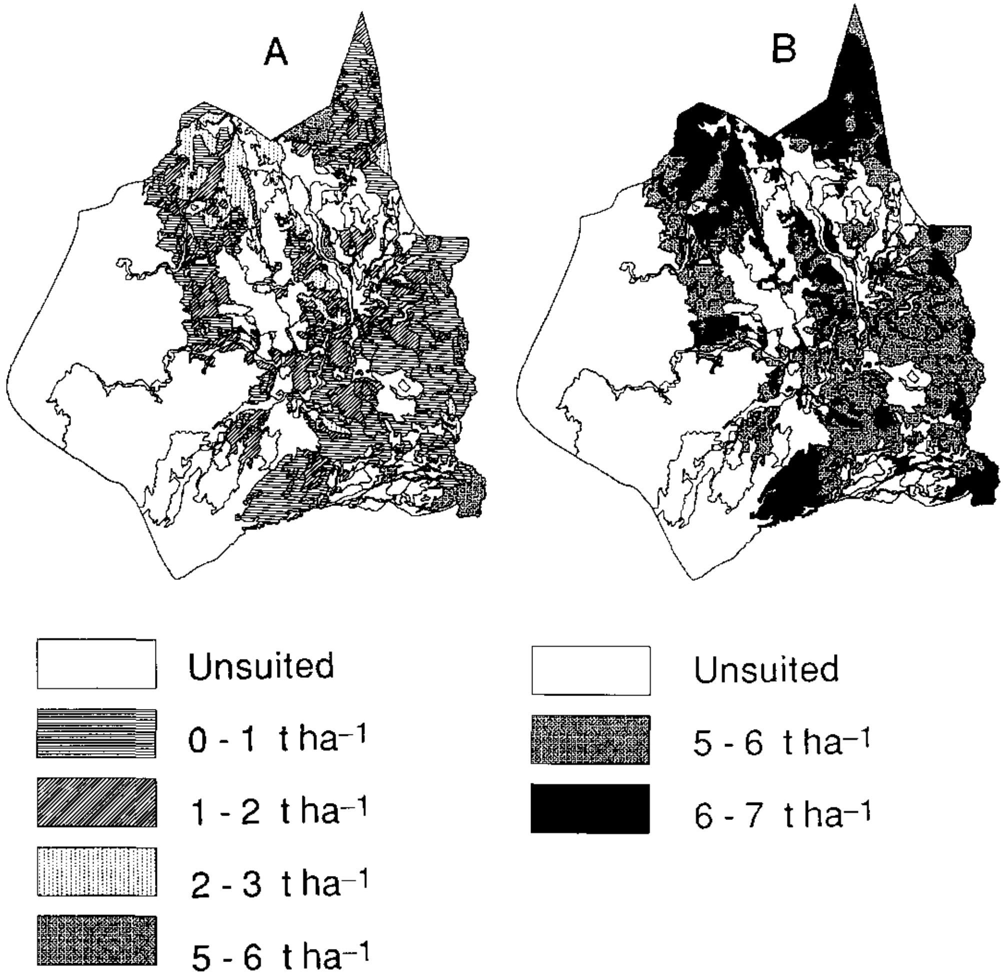

Figure 8. Map of simulated rainfed rice yield (t ha^{-1}) at: (A) 10%; and (B) 90% cumulative probability.

Conclusions and implications

A methodology was presented to quantify rice yield losses due to drought at a regional level. This involves the following steps:

1 Collection of weather data

- Acquire long-term weather data from meteorological stations within the target area or within its immediate surroundings; assign zones to every meteorological station and create a weather map

2 Inventarization of soil data

- Acquire an up-to-date detailed soil map (e.g. from the national soil survey institute)

- If more soil units are distinguished on the soil map than can be sampled: reduce the total number of soil units by generalization, taking into account similarity in soil properties and importance of the unit in terms of surface area.
- Select a representative profile for every (generalized) soil unit.
- Locate every representative profile in the field, guided by the soil map.
- Group soil horizons into hydraulic-functional horizons based on similarity in soil texture and soil structure
- Sample every hydraulic-functional horizon at each representative site.
- Determine hydraulic properties of every hydraulic-functional horizon in the laboratory
- Interpolate to non-sampled areas using the (generalized) soil map
- Estimate course of groundwater table depth throughout the growing season per soil unit.

3 Identification of crop and soil management practices.
4 Identification of soil types that are unsuitable for rice.
5 Estimation of probability distributions of potential (irrigated) and water-limited (rainfed) rice yield for all combinations of suitable soil types and weather zones that occur within the target area using a validated crop-soil model.
6 Display of maps or tables of unsuitable land, irrigated and rainfed crop yields and yield gaps using the GIS software.

The methodology was illustrated with a case study conducted for the Philippine province of Tarlac. Only one weather zone could be distinguished for this province due to paucity of weather data. A sensitivity analysis on the impact of variability in input parameters on simulated rice yields was limited to two important soil parameters: groundwater table depth and saturated hydraulic conductivity of the least permeable layer in the soil profile. Risk involved in growing wet-season rice was quantified for seven major soil types. Production risk was relatively high for large parts of the province. Socio-economic analyses combined with crop modelling are needed to show if alternative land uses (e.g. growing sugarcane instead of rice) can be considered.

Groundwater table depth affected rice yield for some soil types due to capillary rise to the root zone. Long-term data on groundwater table depth are rare. For regional application of models, an estimate of groundwater table depth must be made. Sometimes mottling features in the soil profile can help to identify groundwater fluctuations during the growing season (Moormann & van Breemen, 1978).

The hydraulic conductivity of the least permeable layer in the puddled topsoil was an important determinant of rainfed rice yield for light-textured soils with a relatively permeable subsoil. If no information on this soil parameter is available, a constant percolation rate determined for the various soil types may be used as an input for the soil water balance module PADDY. [Recent experimental results obtained at IRRI (Tuong & Wopereis, unpublished data) showed that lateral percolation losses toward and into bunds, and the effect of poorly puddled spots may be of importance in areas with a relatively permeable subsoil. More complex numerical models that allow for lateral flow into the bunds (e.g. Walker & Rushton, 1984) are needed under these circumstances. On a regional scale, onedimensional models, like the soil water balance module PADDY can still be used, provided a constant percolation rate is assumed, incorporating both vertical and lateral percolation losses.]

Rainfall variability had a very strong impact on yield variability. Field experiments conducted for one or two years in such environments may give misleading results. Long-term weather data are needed to determine probability distributions of crop yield to perform an economic evaluation (Anderson, 1991). Unfortunately in many rice growing countries in Asia there is a lack of long-term weather data as was also the case in this study in Tarlac.

Supplementary irrigation increased wet-season rainfed rice yields and reduced yield variability. Irrigation may also increase the potential for a dry-season crop (e.g. mungbean) which would boost total crop production and income per year relative to rainfed conditions. The scope for a dry-season crop after rice could be investigated using the soil-water balance module PADDY and a good descriptive model for the dry-season crop.

In order to cope with climatic and soil variability, development of well-tested crop growth models and data bases on soil, climate and soil and crop management procedures is required. Coupling such models to a GIS allows spatial analysis of risks. If combined with socio-economic analyses this can be a very powerful tool for policy makers, which may ultimately benefit the farmer.

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Potential and rainfed production of corn in the major agro-ecological zones of Peninsular Malaysia

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Abstract

Potential and rainfed production of corn, cv Suwan I at Bumbong Lima, Sitiawan, Serdang, Kluang and KADA were simulated for sowing on the first day of every month over a ten-year period using the model MACROS to evaluate the potential of corn production in the agro-ecological zones of Peninsular Malaysia. Results show that early year sowings gave higher yields (maximum of 9.56 t ha^{-1} for February sowing in KADA) than late year sowings (minimum of 7.40 t ha^{-1} for October sowing in KADA). The rice growing areas of B. Lima and KADA (zones with clear and dry season) had higher potential yields but with larger variation within the year compared to the other sites. There were large gaps between the potential and rainfed grain yields with < 40% probability of achieving > 5 t ha^{-1} for the rainfed crop for selected sowing dates. Whilst radiation was the main cause for differences in the potential yield between locations, the influence of moisture regime was more important in the case of rainfed yield. Rainfed corn can be grown on paddy soils of B. Lima and KADA in the dry season or between the dry season and the main season rice crop, but with only a yield expectation of 3 t ha^{-1} at 80% probability. On non-paddy soil at Sitiawan (zone with short, but fairly regular dry season), rainfed corn would give low yields, even for the most suitable sowing date (3.5 t ha^{-1} at 80% probability for September sowing) discouraging large scale production unless supplied with irrigation. At Serdang and Kluang (zones with no regular dry season) there is potential for year round production of corn with or without irrigation and as an intercrop with newly replanted rubber.

Introduction

Corn is increasingly becoming an important crop in Malaysia due to a number of reasons. First is the strong growth in the animal industry where corn constitutes the major part of the animal feed. The annual import of corn worth US$ 160 million in 1988 is expected to increase to US$ 400 million by the year 2000 (MARDI, 1990). Secondly, over the years there has been a gradual decline in rice production areas and a corresponding increase in abandoned or idle fields due mainly to labour shortage, unsuitable and infertile soils, water scarcity, pests and uneconomic farm size. The double-cropped rice areas in Peninsular

Malaysia have declined from 250,000 ha to less than 200,000 ha over the last 25 years and are expected to decrease further (MARDI, 1991). Single-cropped rice areas are now less than 100,000 ha compared to 150,000 ha 25 years ago. Thus, substantial areas of paddy land need to be rehabilitated with other crops. Finally, some 40,000 - 50,000 ha of rubber smallholdings are being replanted annually. No yield nor income can be generated from the newly planted rubber trees in the first four years. Cultivation of annual crops in the inter-rows of the young rubber trees is being promoted as this can provide income to the small-holders during the first 2 - 3 years before the trees form a closed canopy. Corn, amongst others, is targeted at all the above areas in addition to the paddy land, that is, to be grown between the rice crops in the dry season.

The objective of this study was to evaluate the potential of corn production in the agro-ecological zones of Peninsular Malaysia, to determine the most suitable planting dates and time frames for grain corn production and to find out if the time frames can fit in with the existing rice cropping calendars. Crop growth modelling was chosen as a tool to do this.

Material and methods

The models used are based on the model MACROS of Penning de Vries et al. (1989), adapted and validated for the potential and rainfed production of grain corn (Wan Sulaiman & Rushidah, 1991a, b). The model for potential production comprised the basic module for crop growth simulation with daily time step, L1D of MACROS and the crop data for cv. Suwan I derived from basic physiological data cited by Penning de Vries et al.(1989) and from a field experiment reported by Wan Sulaiman & Rushidah (1991b). The model was driven by daily weather data consisting of the maximum and minimum temperatures as well as solar radiation expressed in sunshine hours.

The model for rainfed production, was assembled by combining the module L1D with the L2C module for simulation of canopy transpiration, the module L2SS (Sawah) for water flow in soils with impeded drainage and the crop data for cv. Suwan I. Daily rainfall, humidity and wind speed were also required in addition to those specified for the potential production model. The modeule L2SS enabled a comparison to be made between crop growth on rice soils having a hard pan and a shallow water table with the freely draining but low permeability upland soils. The simulated and observed values of different crop components for the rainfed growth of corn sown on 20 November 1989 at Serdang are shown in Figure 1.

Five sites were chosen for the study. These are Bumbong Lima (or B. Lima), Sitiawan, Serdang, Kluang and KADA which are located in four lowland agro-climatic zones of Peninsular Malaysia and represent three types of agro-ecological regions. B. Lima and KADA represent regions with a clear and regular dry season, Sitiawan represents regions with a short but fairly regular dry season while Serdang and Kluang represent regions without a regular dry season. The main features of the sites are given in Table 1. Each site had its own meteorological station from which the weather data for simulation modelling

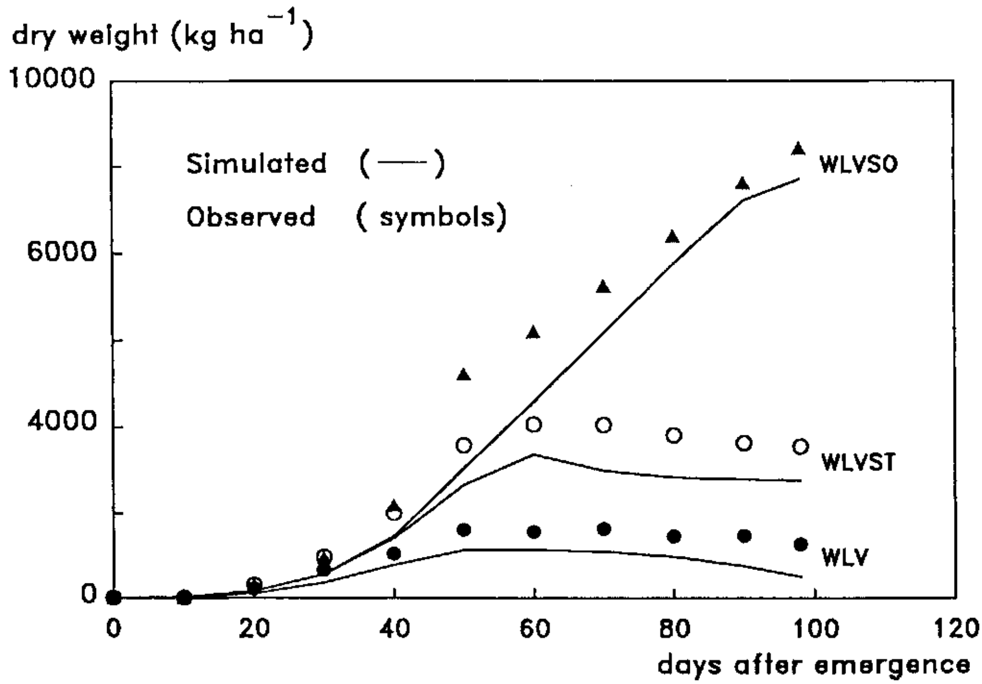

Figure 1. Simulated and observed biomass (dry weight, kg ha^{-1}) of above-ground parts of rainfed corn cv. Suwan I sown in November 1989 at Serdang. WLV is the weight of the leaves; WLVST is the weight of all leaves plus stems (including leaf sheaths) and WLVSO is the total above-ground biomass.

were taken (see Figures 3 and 4).

Both potential and rainfed production at the five sites were simulated for sowing on the first of every month over 10-year periods, 1982 - 1991 for KADA and 1979 - 1988 for the other four sites. In simulating and comparing rainfed yields, two soil types were used that were typical for the agro-ecological environments of the five sites. For B. Lima and KADA in the rice areas, the 'lowland rice' soil consisted of 20 cm sandy clay loam (scl) overlying 10 cm silty clay (sic) plow pan of low permeability and 70 cm silty clay. At Sitiawan, Serdang and Kluang, the 'upland' soil was made up of 20 cm sandy clay loam overlying 80 cm sandy clay (sc). B. Lima and Serdang were used as 'benchmark' sites for the lowland and upland situations respectively. At these sites, soil parameters to describe the pF curve and the hydraulic conductivity curve of the various soil layers were derived from measurements. The pF curve was described by the relationship as given by Driessen (1986):

$$w = w_s \bullet \exp -(c \ln^2 |h|) \qquad (1)$$

where w is the (volumetric) soil water content, w_s the saturated water content, h the soil water pressure in cm and c, a constant. The hydraulic conductivity (k) curve was described by the relationship as given by Rijtema (1969):

Table 1. Details of the five study sites covering four agro-climatic zones of Peninsula Malaysia.

Site	Location	Agro-ecology[1]	Soil	Land use
Bumbong Lima	5° 32' N 100° 28' E North-west agro-climatic zone	Clear and regular dry season, Dec - March and less clear secondary dry season around July	Marine and riverine alluvia, medium to heavy texture	Rice - part of north-west rice bowl
Sitiawan	4° 13' N 100° 38' E West coast agro-climatic zone	Short but fairly regular dry season, June-July and less clear secondary dry season around February	Sedentary and riverine Inceptisols and Ultisols, medium to heavy texture on flat to gently undulating topography	Permanent crops - rubber, oil palm interspersed with mixed crops
Serdang	2° 59' N 101° 04' E West coast zone	No regular dry season, but two periods of less rainfall, May - August and around February	Sedentary Oxisols, Ultisols and Inceptisols, medium to heavy texture on gentle to undulating topography	Rubber, oil palm and fruits interspersed with annual crops
Kluang	2° 04' E 103° 04' E South agro-climatic zone	No regular dry season, but short irregular dry spells in Jan-March, June-Aug, less sunshine in Dec.	Sedentary Oxisols and Ultisols, medium to heavy texture on rolling topography	Oil palm and rubber
KADA	6° 05' N 102° 12' E East coast agro-climatic	Clear and regular dry season, heavy monsoon rain Oct - Dec followed by dry season, Jan till April	Soils developed on river terraces of Kelantan flood plain, medium to heavy texture	Rice - centre of the north-east rice bowl

[1] After Nieuwolt et al. (1982)

$$k = k_s \bullet \exp -a\,|h| \qquad (\,|h| < |h|_{max}\,) \tag{2a}$$

$$k = b \bullet |h|^{-1.4} \qquad (\,|h| > |h|_{max}\,) \tag{2b}$$

where k_s is the saturated hydraulic conductivity in cm d^{-1}, a, b and $|h|_{max}$ are constants. Parameter values of Equations 1 and 2 for the soil layers at B. Lima and Serdang are given in Table 2. The water tables in the 'lowland' rice soils at B. Lima and KADA were estimated from the respective rainfall distributions and miscellaneous reports. Their depths, ZWTB as functions of daynumber of the year in CSMP notation were

Bumbong Lima:
FUNCTION ZWTB = (1, 2.0), (90, 1.5), (150, 1.75), (210, 1.6), (240, 1.0), (366, 2.0)
KADA:
FUNCTION ZWTB = (1, 1.5), (30, 2.0), (90, 2.0), (270, 1.3), (330, 0.6), (366, 1.5)

The first value in each pair (within the parentheses) represents the daynumber of the year and the second, the water table depth in m. Water table at the three other (upland) sites was deep and set to > 3 m in the model. In all cases, the maximum rooting depth was set at 30 cm because corn roots rarely extend beyond this depth in the acid soils of Malaysia (Sharifuddin, personal communication). Partial root impedance was mimicked by halving the rate of root length extension once the root has extended beyond the 15 cm plough layer.

Table 2. Parameters for the soil moisture characteristics and hydraulic conductivity functions (Equations 1 and 2) of different soil layers, as derived from field measurements.

Location and Soil layers	Texture	w_s ($cm^3\,cm^{-3}$)	c (-)	k_s (cm d^{-1})	a (cm^{-1})	b ($cm^{2.4}\,d^{-1}$)	$\lvert h\rvert_{max}$ (cm)
Bumbong Lima:							
0 - 20 cm	sandy clay loam	0.445	0.0051	3.5	0.0248	1.69	300
20 - 30 cm	silty clay	0.507	0.0059	0.2	0.0480	28.20	50
30 - 100 cm	silty clay	0.540	0.0043	1.0	0.0380	4.86	80
Serdang:							
0 - 20 cm	sandy clay loam	0.445	0.0051	20.0	0.0248	1.69	300
20 - 100 cm	sandy clay	0.507	0.0059	3.5	0.0480	28.20	50

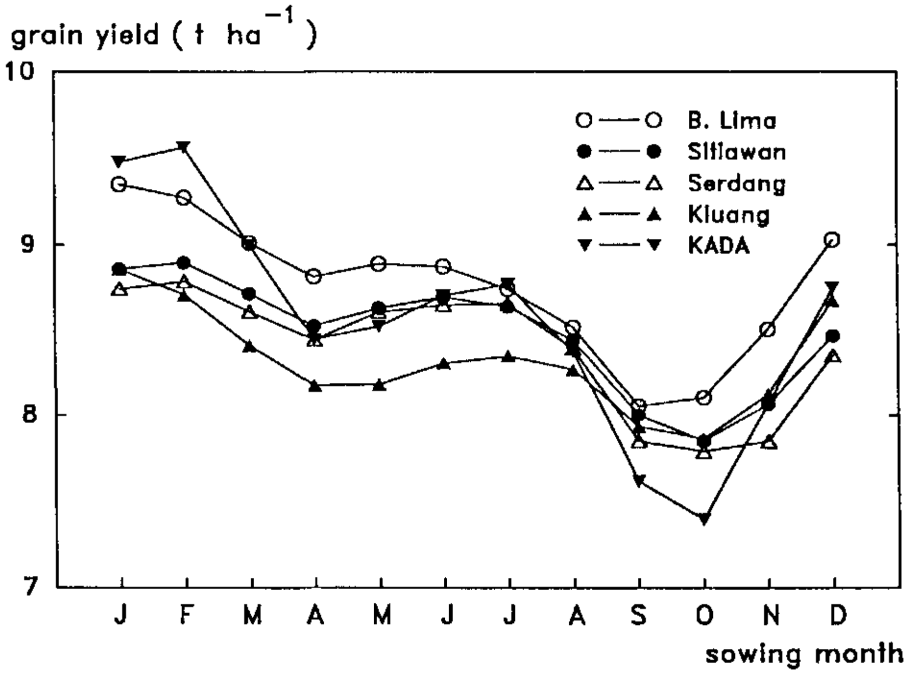

Figure 2. Ten-year mean simulated potential yield of corn cv. Suwan I for different sowing dates at five locations representing different agro-climatic zones of Malaysia.

Results and discussion

Potential production

The 10-year mean simulated potential grain yields of grain corn at the five sites when sown on the first day of every month are shown in Figure 2. The two northern sites, B. Lima and KADA had the highest potential yields as well as the largest variation over the year. Early year sowing gave higher yields than late year sowing, with the highest yield coming from the February sowing for all the five sites and the lowest from the October and November sowings. The highest mean yield was 9.56 t ha^{-1} achieved with the February sowing in KADA and the lowest was 7.40 t ha^{-1} for the October sowing, also in KADA. The high potential yields early in the year were associated with more sunshine hours and slightly lower mean temperatures particularly in KADA and B. Lima (Figures 3 and 4). Conversely, the low potential yields late in the year were attributed to less sunshine hours. Serdang and Sitiawan showed the least variation in yield because of the more uniform sunshine and temperature distribution over the year.

Rainfed production

The simulated yields of the rainfed corn at 20%, 40%, 60% and 80% probability levels for the five sites are given in Figure 5. Also shown are the rainfall distribution at 80% level of probability expressed as percent of the potential evapotranspiration (E_0) based on the 25-

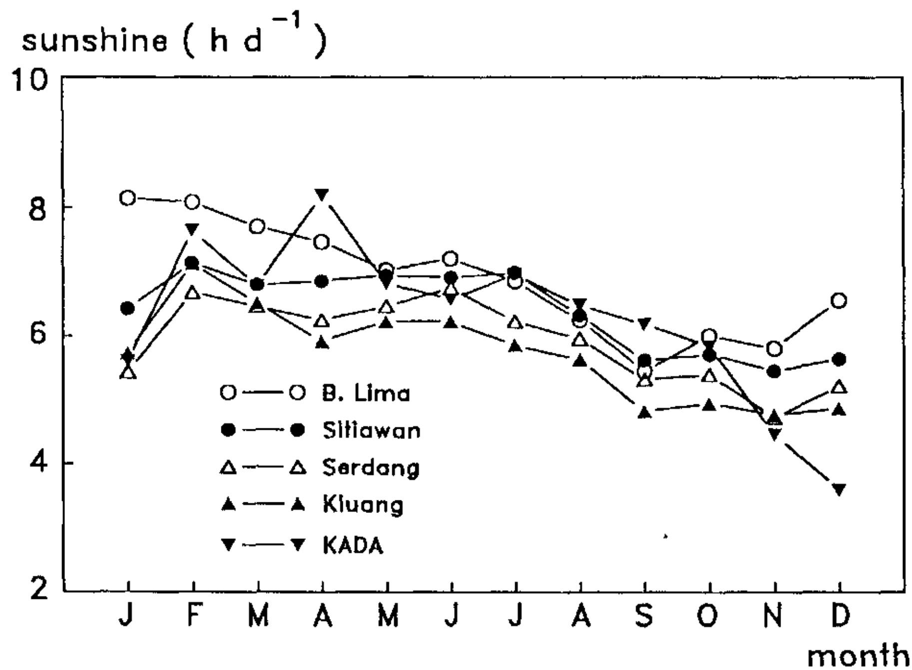

Figure 3. Ten-year mean daily hours of sunshine throughout the year at five locations in Malaysia - Bumbong Lima, Sitiawan, Serdang, Kluang and KADA.

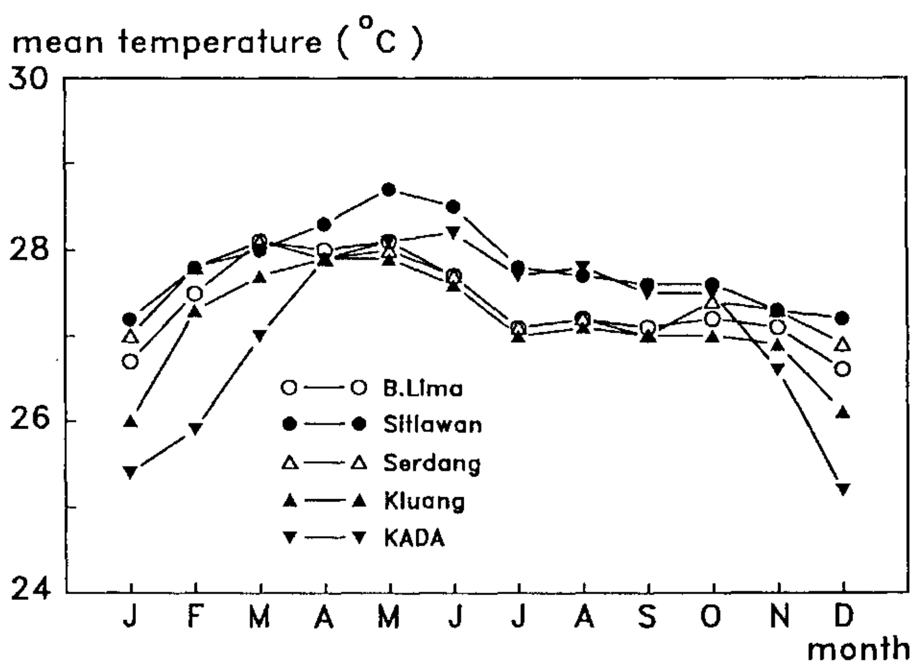

Figure 4. Ten-year average daily temperature throughout the year at five locations in Malaysia - Bumbong Lima, Sitiawan, Serdang, Kluang and KADA.

year period, 1951 - 1975 (Nieuwolt et al., 1982) (for most rainfall stations in Malaysia, E_0 varies between 100 mm month^{-1} and 130 mm month^{-1}). For all sites, the rainfed yields were well below their potential yields. The yield pattern over the whole year was more related to the rainfall than to the radiation and temperature. Yields higher than 5 t ha^{-1} were possible but with a low probability (40% or less) and only for selective sowing months.

In many agricultural enterprises a risk of insufficient rainfall of about 20% is acceptable. Conversely, the yield that may be expected at 80% probability can be used to assess project viability. The potentials at each site are briefly described below.

Bumbong Lima There are five sowing months available in a year (April - September) for achieving yields greater than 3.0 t ha^{-1} (with 80% probability). Two crops can be grown, one in April and the second in August or September. If the critical or desired yield were to increase to 3.5 t ha^{-1}, only one crop is possible, i.e., July sowing. Early year sowings are affected by insufficient rainfall (<40% of E_0) while those from late year sowing suffer waterlogging followed by drought. Experimental yields of 4.9 - 5.8 t ha^{-1} have been obtained for crops sown in April, May and August on a non-paddy soil of similar texture at nearby Bertam (Zainudin, 1987). Leong & Wan Sulaiman (1992) on the other hand reported grain yields of 2.0 - 3.5 t ha^{-1} from five seasons of grain corn sown in April and September in a pilot project on abandoned rice soil at nearby Kg. Padang Tembusu.

Sitiawan There are only five non-water deficit months where rainfall exceeds E_0, i.e., in April and September through to December. This condition is well reflected in the yield distribution where only the September - December sowings produced yields higher than 3.0 t ha^{-1} with an 80% probability. Pilot projects carried out by MARDI at this location produced yields of 1.6 - 3.2 t ha^{-1} (Leong, 1991).

Serdang All sowings except those of May to July resulted in grain yields higher than 3 t ha^{-1}. There is adequate rainfall during most of the year. Even the drier months of January - February and May - August receive rainfall that exceed 60% of the E_0. Three rainfed crops can be sown in a year, in April, August and December. Razak (1989) reported an experimental yield of 5.0 t ha^{-1} for Suwan I sown on 15.8.1988 on a soil of similar texture while Anuar (1991) reported stable experimental grain yields of 5.27 - 6.84 t ha^{-1} of sweet corn (crop duration of about 85 days) when sown in March and September which are also the most favourable sowing months as shown in the present study.

Kluang Apart from December, January and May sowings, grain yields were greater than 3.0 t ha^{-1}. Three crops are possible in a year, sown in March, July and November, but the most favourable months appear to be April and September.

KADA The performance of grain corn in KADA was poorer than in B. Lima. Only one crop, sown in July - September, yielded higher than 3.0 t ha^{-1}. Similar to B. Lima, early year sowings will suffer severe water stress where rainfall during five consecutive months

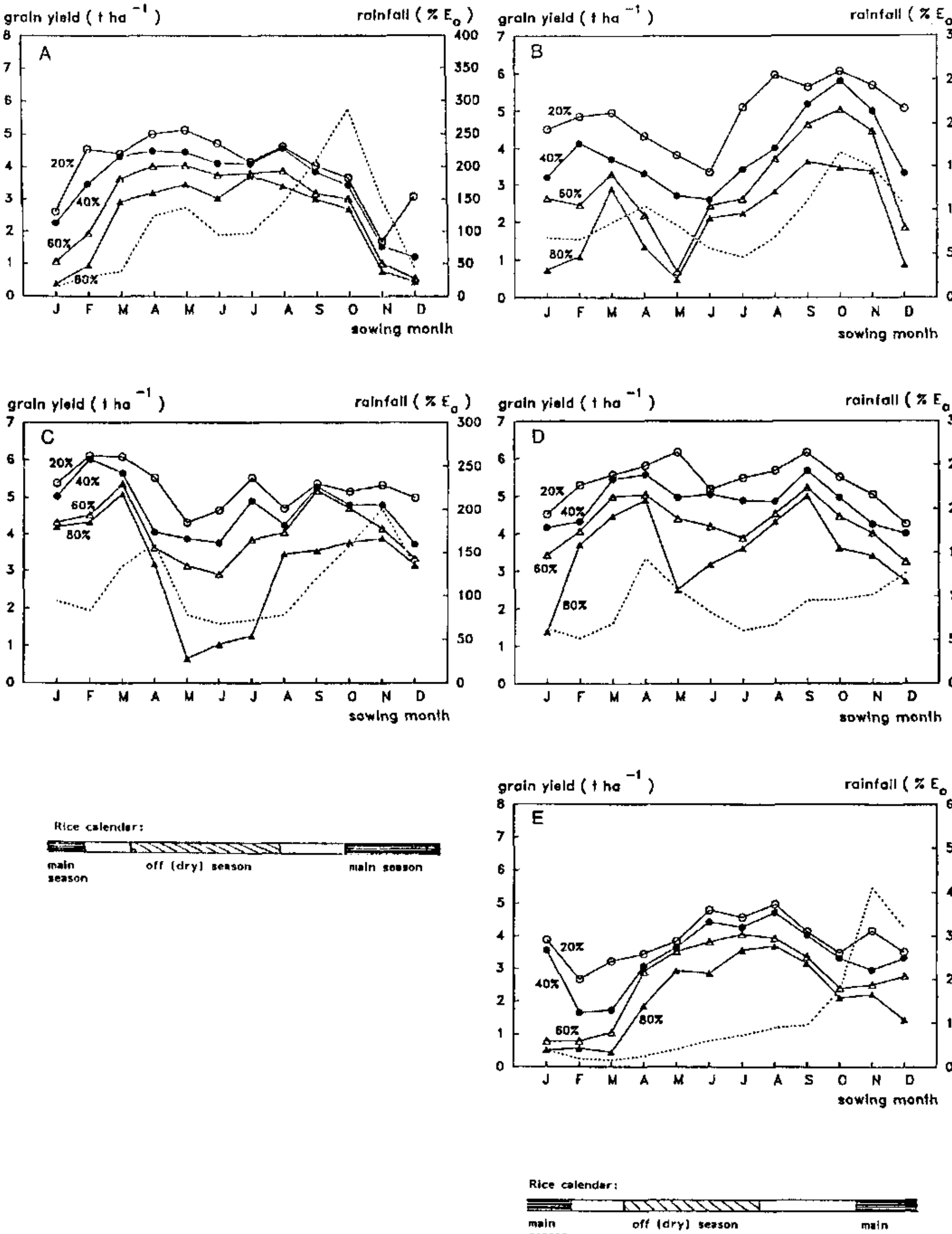

Figure 5. Simulated rainfed yield of corn cv. Suwan I at 20%, 40%, 60% and 80% probability levels for different sowing months and the associated rainfall at 80% probability (dashed line) at different locations in Malaysia: (A) Bumbong Lima, (B) Sitiawan, (C) Serdang, (D) Kluang and (E) KADA.

from January till May amount to less than 50% of E_0, while late year sowings will experience waterlogging from the excessive rain (160 - 400% of E_0).

Corn-after-rice

For Bumbong Lima, the simulated corn cropping calendar fits in well with the current rice calendar (Figure 5A). Following the single (main) season rice crop from September to February, grain corn can be sown in March/April and harvested by July with a 60% probability of attaining a grain yield in excess of 3.5 t ha^{-1}. Alternatively, one crop of grain corn followed by a crop of sweet corn for table consumption could be grown and harvested by August and still permit sufficient time for field preparation for next year's rice crop. In single rice crop areas of KADA, grain corn can be sown in July, after a 5-month fallow following the rice crop, and harvested in late September or early October before the next rice crop (Figure 5E). A yield of 3.5 t ha^{-1} can be expected at 80% probability.

The 100 - 110 days growth duration required by a crop of grain corn does not permit it to be grown between the two rice crops in double-cropped areas. Thus, sweet corn for table consumption, which requires only 60 - 65 days from sowing to harvest is considered instead. In this case, it is assumed that sowing dates that are suitable for grain corn are also suitable for sweet corn. In KADA, the optimum sowing month for corn is August and, therefore, fits in very well with the existing planting schedule for rice (Figure 5E). Adequate and well distributed rainfall in August till October allows for the corn to be grown before planting of the next rice crop in November. This would enhance the income of rice farmers. However, cultural operations would need to be hastened so as to complete land preparation for seeding of the rice crop immediately upon the corn harvest. In B. Lima and the Muda Agricultural Development Area further north, it is also possible to have a crop of sweet corn between the two rice seasons. The crop can be sown in July/August after the harvest of the dry season crop and harvested in October but this would require a shift in the planting of the main season rice from September/October to October/November (Figure 5A).

Conclusion

There are large gaps between the potential and rainfed yields at all locations studied particularly for early year sowing in the North and East Coast agro-climatic zones. The possibility of early year planting in these zones should be pursued by looking towards non-paddy soils and providing sufficient inputs, especially irrigation water. The yield prospects are good as shown by Ungku Ismail (personal communication) who obtained a yield of 9.9 t ha^{-1} in a maximum yield trial (irrigated) on a non-paddy soil in the KADA region. Rainfed corn can be grown on paddy soils in the off-season (dry season) or between the off-season and main season rice crops but with a low probability of attaining high yields. Thus, irrigation is strongly recommended.

In coastal areas of the central West Coast Zone with conditions similar to Sitiawan, rainfed corn will give relatively low yields even for the most suitable sowing dates. Therefore, large scale production of corn should be provided with irrigation. In inland areas of the West Coast and South zones, there is potential for year round production of corn with or without irrigation. However, large scale production is constrained by availability of land and the best option is for it to be grown as an intercrop with newly planted or replanted rubber. In this case, sweet corn for table consumption is a better prospect than grain corn.

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Uncertainty in soil and management parameters in crop growth modelling on regional scale

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Abstract
A framework was developed for crop yield simulation on a regional scale that accounts for uncertainty in soil and management parameters. The land-unit, which is a combination of homogeneous soil type and weather characteristics, is the basic unit of simulation. The framework consists of three steps: 1) the calculation of temporal yield probability using average estimated soil and management parameters; 2) sensitivity analysis to relate input parameter accuracy to simulated yield accuracy; 3) the calculation of spatial yield probability from probability distributions for soil and management parameters by using Monte Carlo simulation. The combination of temporal probability of step 1 with spatial probability of step 3 gives the overall yield probability. The results of step 2 are useful in determining efficient and cost-effective measurement strategies. The framework is illustrated for rainfed upland rice on a loamy soil in the Philippines, using the crop growth model MACROS. Results of each case study are specific for the used simulation model and environment and the framework should be repeated for other situations.

Introduction

Crop growth simulation models are increasingly being used to assess yield potentials on regional to global scales (Buringh et al., 1979; van Keulen & Wolf, 1986; van Lanen, 1991; van Diepen et al., 1991; Hammer & Muchow, 1991). A major problem in these (supra-) regional studies is how to derive and deal with the input data that are needed to run the simulation models. Crop specific input parameters generally 'come with the model' but are best to be validated on well-defined field experiments within the region of application. Examples of crop specific parameters are development rate, relative growth rate, light use efficiency and leaf photosynthesis rate. Another set of model input requirements are environmental parameters that need to be collected for the specific area under study: weather, soil and management parameters. Examples of weather parameters are solar irradiation, temperature and rainfall; examples of soil parameters are water retention and hydraulic conductivity curves; an example of a management parameter is sowing date. Weather data are collected at meteorological stations. Problems and solutions regarding matters such as spatial interpolation, the treatment of missing and of average data, and the use of weather generators in relation to crop growth modelling have been reported extensively (van Keulen & Wolf, 1986; Penning de Vries et al., 1989; Reinds et al., 1991; Geng et al., 1986; Beek, 1991a, b). The most accurate information on soil parameters is obtained from actual field observations, soil sampling and subsequent *in situ* or laboratory measurements (Cochran, 1977; Webster, 1985; Stein, 1991; Bregt, 1992). However, such measurement programmes are often restricted because of high cost and time and labour requirements involved. In recent research, Wopereis et al. (1993a, b) have emphasized the importance of 'tuning' the measurement strategy for soil properties to the specific input and output requirements of the simulation model. In practice, a much followed course is to estimate average soil parameters for more or less homogeneous land-units from available information on soil maps (Reinds et al., 1991; van Lanen, 1991). Much research has been (and still is) dedicated to so-called pedotransfer functions that relate soil parameters to soil properties that are generally available such as soil texture and depth (Driessen, 1986a, b; Bouma & van Lanen; 1987; Ritchie & Crum, 1989; van Genuchten et al., 1989). Average management parameters for homogeneous land-units are mostly derived from expert knowledge. The estimated soil and management parameters are then used to predict crop yield in years for which weather data are available or have been generated. Though this procedure is a valid practical approach in itself, generally no or little information is presented on the accuracy in predicted yield in relation to the uncertainty in the estimated parameter values. The reliability of such predicted yields is often difficult to assess, which gives rise to questions about the validity of the simulation approach. Clearly, there is a need for methodologies to deal with uncertainty in soil and management parameters in regional yield simulation, which is the subject of this paper.

A framework will be presented for crop yield simulation on regional scales which accounts for the effects of uncertainty in soil and management parameters. Two major issues are addressed:

1 The need for procedures to set up efficient and cost-effective sampling strategies to meet model input and output requirements, and
2 The need for quantifying the effect of uncertainty in estimated soil and management parameters on simulated crop yield.

The framework will be illustrated for a case study of rainfed upland rice in the Philippines, using the growth model MACROS (Penning de Vries et al., 1989). Problems related to the actual acquirement of environmental input data, and to the spatial presentation of simulated yield are the subject of ongoing research and fall outside the scope of the present paper.

Outline of the framework

In line with current, practical approaches in regional yield simulation, the framework uses land units that are unique combinations of homogeneous soil types and weather characteristics as basic units of modelling. Weather data are obtained from a meteorological station, soil input data are estimated from information on soil maps and management parameters are derived from expert knowledge. The framework consists of three steps.

Step 1 Crop yield for a land unit is simulated using the average estimated soil and management parameters for all years that weather data are available. The estimated average parameter set will be called 'standard' set and the simulated yields are 'standard' yields. The resulting set of simulated standard yields represents the temporal yield probability.

Step 2 From the available years of weather data, a number of the 'best' and 'worst' years are selected based on the simulated standard yields. For these years, sensitivity analysis is carried out on the soil and management input parameters. For each year, the simulated yield is normalized to standard yield for comparison on a similar basis: yield factor. The relationships between deviation in yield factor and deviation in input parameter values is calculated. These relationships indicate the type of input parameters that significantly affect simulated crop yield, and relate the accuracy with which these parameters need to be collected to the (desired) accuracy of the simulated crop yield. These results are useful for designing efficient sampling and measurement strategies.

Three points have to be considered in setting up a sensitivity analysis:

1 Which parameters need to be included? When no prior knowledge about the relative significance of the input parameters is available, all parameters should be included. Else, only the known relevant parameters are selected.
2 What is the range in parameter values? The ranges of the parameter values should be taken as broad as possible to make sure that the actual values in the area under study are covered. The boundary values can be taken from initial survey data, from expert knowledge, from literature or from any reasonable guess, as long as the values are not beyond the validity domain of the model.
3 What is the correlation between parameters? Input parameter values can not indiscriminately be varied without considering the values of (some of) the other input parameters (i.e. *ceteris paribus*). Correlation between parameters may exist and should be dealt with.

Step 3 For every soil and management parameter that has a significant impact on simulated yield (as found in Step 2) the uncertainty in the standard value is quantified by estimating a probability distribution. Probability distributions can be derived from expert knowledge, literature data, actual measurements or any other source of information. When no probability distribution can be estimated, a uniform distribution between plausible boundary values should be used. Monte Carlo (MC) simulation is used to calculate N crop yield values from N combinations of the input parameter values that are chosen at random from their probability distributions. MC simulation is carried out for a number of the best, average and worst years and the yield factor is calculated. The resulting sets of N simulated yield factors represent the spatial yield probability.

The three steps of the framework form an integral package. For each level of simulated standard yield in Step 1 - which is characterized by a temporal probability - a corresponding spatial probability is found in Step 3. When the spatial yield probability does not meet the accuracy requirements of predicted crop yield, the results from Step 2 indicate the type and accuracy of soil and management parameters that need to be collected.

The case study

Simulation model and environment

The yield of rainfed upland rice was simulated for a land-unit with a deeply developed, homogeneous, freely draining loamy soil in the Philippines. Upland rice is direct-seeded on non-puddled soil. The crop growth model used was MACROS as described by Penning de Vries et al. (1989) and Herrera-Reyes & Penning de Vries (1989). From the MACROS modules, the growth module L2D was combined with the water balance SAHEL for freely draining soils. In this configuration, nutrients are supposed to be in ample supply, and the crop is free from pests, diseases and weeds. The simulations were carried out for rice variety IR36 with a medium growth duration. Crop specific input data for this variety are given by Penning de Vries et al. (1989; p. 212).

Environmental input data

Weather input data: for the calculation of rainfed crop yield, MACROS needs daily values of solar irradiation, minimum and maximum temperature, rainfall, relative humidity and average wind speed. The weather data were taken from 26 years of daily observations between 1959 - 1984 by the University of the Philippines, Los Baños.

Soil input data MACROS-SAHEL soil input parameters were estimated from the soil description using the standard values for a loamy soil as given by Penning de Vries et al. (1989; pp. 218) for all soil layers (Table 1). The initial water content at the start of simulation was 100% of field capacity. As in a typical upland situation, the water table was assumed to be very deep with no capillary rise to the rooting zone. Because the soil was deeply developed, no impediments to root growth were assumed and the roots could extend to the maximum depth for upland rice (90 cm).

Management parameter Rainfed rice production was simulated for the wet season (June-October). Based on expert-knowledge, the start day of simulation (DATEB) was set to calendar day 197.

Sensitivity analysis and correlation between parameters

From the soil parameters in Table 1, the water content values at different pressure heads are correlated parameters. For these parameters, relationships were derived to account for the mutual correlation (see below). The ranges for sensitivity analysis were chosen to include values for sandy loam to clay as given by Penning de Vries et al. (1989; p. 218) (Table 1). The other soil parameters were considered non-correlated and were varied under *ceteris*

Table 1. Abbreviation and explanation of the soil input parameters for MACROS with the SAHEL water balance, and of the management parameter 'start day of simulation'. Standard estimated values are given for a loamy soil and for the average start date of crop growth in the wet season, Los Baños, the Philippines, also the ranges used for the sensitivity analysis are given.

Abbr.	Explanation	Standard	Range	Unit
Soil parameters				
WCST	water content saturation	0.50	0.40-0.55	$cm^3\ cm^{-3}$
WCFC	water content field capacity (pF 2)	0.36	0.25-0.50	$cm^3\ cm^{-3}$
WCWP	water content wilting point (pF 4.2)	0.11	0.05-0.35	$cm^3\ cm^{-3}$
WCAD	water content air dry (pF 7)	0.01	0.00-0.20	$cm^3\ cm^{-3}$
WCLI	initial soil moisture content	0.36	0.10-0.36	$cm^3\ cm^{-3}$
RFSD	reflection coeff. dry soil	0.20	0.10-0.40	-
WDCL	width of soil clods	0.05	0.01-0.10	m
EES	extinction coeff. evaporation	20	5-35	-
Management parameter				
DATEB	start day simulation	197	167-227	d

paribus conditions. The ranges for these soil parameters were chosen to cover general ranges reported for sand to clay soils (Table 1). The range for start day of simulation was set to plus/minus one month around the average (Table 1).

Water retention curves give the relationship between soil water content ($S(h)$) and hydraulic pressure head (h). In MACROS, the following equation as presented by Driessen (1986a, p. 81) is used to describe water retention curves for different soil types:

$$S = S_0 \bullet \exp(-\gamma \bullet (\ln|h|)^2) \qquad (1)$$

in which S_0 and γ are empirical parameters that are specific for texture and bulk density. This equation has been parameterized for soils in The Netherlands that were categorized into 20 textural soil types ranging from coarse sand through loam and heavy clay to peat (Driessen, 1986a). These values are used as default in MACROS when no actual measurements are available (standard input parameter values). Using the parameterized equations, water content values at saturation (WCST), field capacity (WCFC), wilting point (WCWP) and air-dryness (WCAD) were calculated for all 20 soil types and plotted against each other (Figure 1). Except for the peat soil, all data points appeared correlated without differentiation to soil texture class. The following empirical equations were derived to relate WCST, WCWP and WCAD to WCFC:

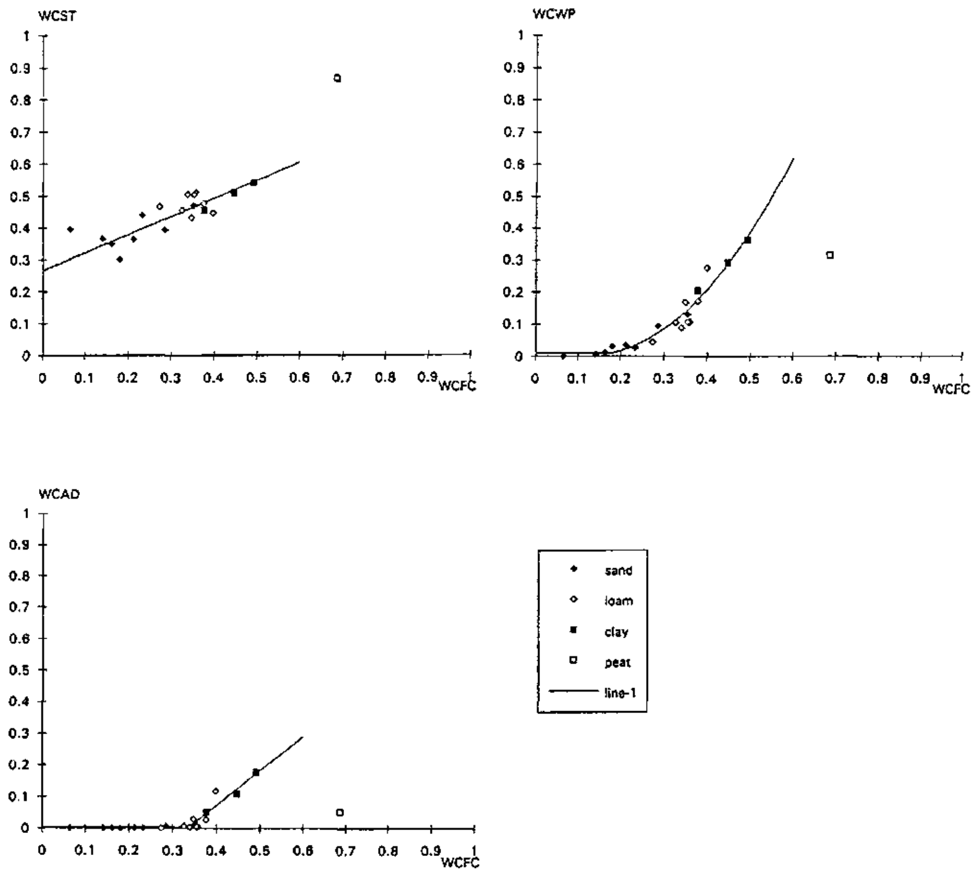

Figure 1. Water content at saturation (WCST), at wilting point (WCWP) and at air-dryness (WCAD) versus water content at field capacity (WCFC) for sand, loam, clay and peat soils (soil data from Driessen, 1986a). The drawn lines are the fitted empirical relations.

$$\mathrm{WCST} = 0.265 + 0.564 \cdot \mathrm{WCFC} \qquad (2)$$

$$\mathrm{WCWP} = 0.046 - 0.691 \cdot \mathrm{WCFC} + 2.749 \cdot \mathrm{WCFC}^2 \qquad (3)$$

(with $\mathrm{WCWP}_{\mathrm{minimum}} = 0.005$)

$$\mathrm{WCAD} = -0.366 + 1.095 \cdot \mathrm{WCFC} \qquad (4)$$

(with $\mathrm{WCAD}_{\mathrm{minimum}} = 0$)

WCFC was used as 'explanatory' variable because it can relatively easily be measured in the field. From the overall ranges set for sensitivity analysis (Table 1), subranges were created for each water content parameter. The above equations were used to calculate average corresponding values for the other water content parameters (Table 2). The sensitivity analyses using these parameter ranges and values were performed under *ceteris paribus* conditions for the other soil parameters except for the initial moisture content (WCLI). WCLI was always taken as 100% of the water content at field capacity.

Table 2. Ranges used for WCST, WCFC, WCWP and WCAD in sensitivity analyses. The mean values for the corresponding water content parameters that remained unchanged during the analyses were calculated from Equations 2 - 4.

WCST		Corresponding water contents		
Range	Average	WCFC	WCWP	WCAD
0.40-0.50	0.45	0.33	0.12	0.005
0.45-0.55	0.50	0.42	0.24	0.09
WCFC		**Corresponding water contents**		
Range	Average	WCST	WCWP	WCAD
0.25-0.35	0.30	0.43	0.09	0
0.30-0.40	0.35	0.46	0.14	0.02
0.35-0.45	0.40	0.49	0.21	0.07
0.40-0.50	0.45	0.52	0.29	0.13
WCWP		**Corresponding water contents**		
Range	Average	WCST	WCFC	WCAD
0.05-0.15	0.10	0.44	0.31	0.005
0.10-0.20	0.15	0.47	0.36	0.03
0.15-0.25	0.20	0.49	0.40	0.07
0.20-0.30	0.25	0.51	0.43	0.11
0.25-0.35	0.30	0.52	0.46	0.14
WCAD		**Corresponding water contents**		
Range	Average	WCST	WCFC	WCWP
0.005-0.10	0.05	0.48	0.38	0.18
0.05 -0.15	0.10	0.51	0.43	0.26
0.10 -0.20	0.15	0.53	0.47	0.33

Results of the case study

Step 1 temporal yield probability

With the standard soil and management parameter values (estimated averages for the land unit), rainfed rice yield was simulated for all 26 years of weather data. Figures 2A and B give the temporal yield probability and the cumulative temporal yield probability respectively. The average rainfed yield was 3.06 t ha^{-1}, with 80% of the yields between 2.5 and 3.7 t ha^{-1}. For reference, the potential, irrigated rice production for this environment was predicted to be 6.5 - 7.5 t ha^{-1} (80% probability).

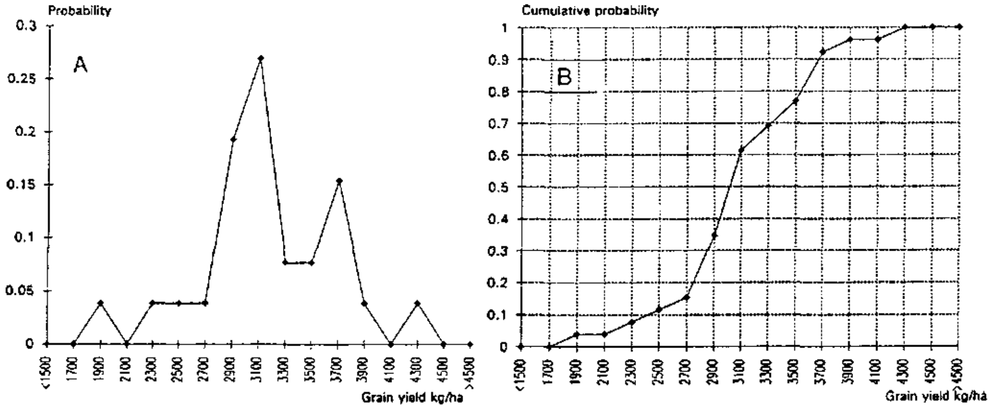

Figure 2. Temporal yield probability (A) and cumulative temporal yield probability (B) of predicted upland rice yield with Los Baños weather data from 1959 - 1984, using the standard input parameters given in Table 1.

Step 2: sensitivity analysis

Sensitivity analysis was performed for the three best years (1961: 4.1 t ha^{-1}; 1976: 3.7 t ha^{-1}; 1963: 3.6 t ha^{-1}) and the three worst years (1983: 2.5 t ha^{-1}; 1982: 2.2 t ha^{-1}; 1972: 1.9 t ha^{-1}). The simulated yields in a given year were normalized to the simulated standard yield in that year: yield factor is the simulated yield with given input value divided by simulated yield with standard input values. The results of the sensitivity analyses are given in Figure 3.

For most soil parameters, the sensitivities were similar for the different years. For the water content parameters, they were also similar for different soil texture classes. The effect of WCST, WCFC and WCWP on yield factor was relatively large (Figures 3A/C), while there was virtually no effect of WCAD (Figure 3D). Only for yield factors above 1.25 did differentiation between the years occur for WCST and WCFC. For these two parameters, the three best years had mutually similar trends, whereas the worst years had deviating patterns.

Decreasing values of initial moisture content (WCLI) resulted in decreasing yield factor, though the magnitude of this decrease was year-specific (Figure 3E). The general trend was that yield factor first slowly decreased when WCLI dropped from 0.36 to about 0.27 (i.e. from 100 to 75% of WCFC), and then decreased more steeply when WCLI dropped further.

The parameters 'reflection coefficient dry soil' (RFSD), 'width of soil cloth' (WDCL, not shown) and 'extinction coefficient for evaporation in soil' (EES) had no effect on the yield factor (Figures 3F/G).

The sensitivity of yield factor to start day of simulation (DATEB) varied somewhat between the years because of (minor) differences in rainfall patterns (Figure 3H). There

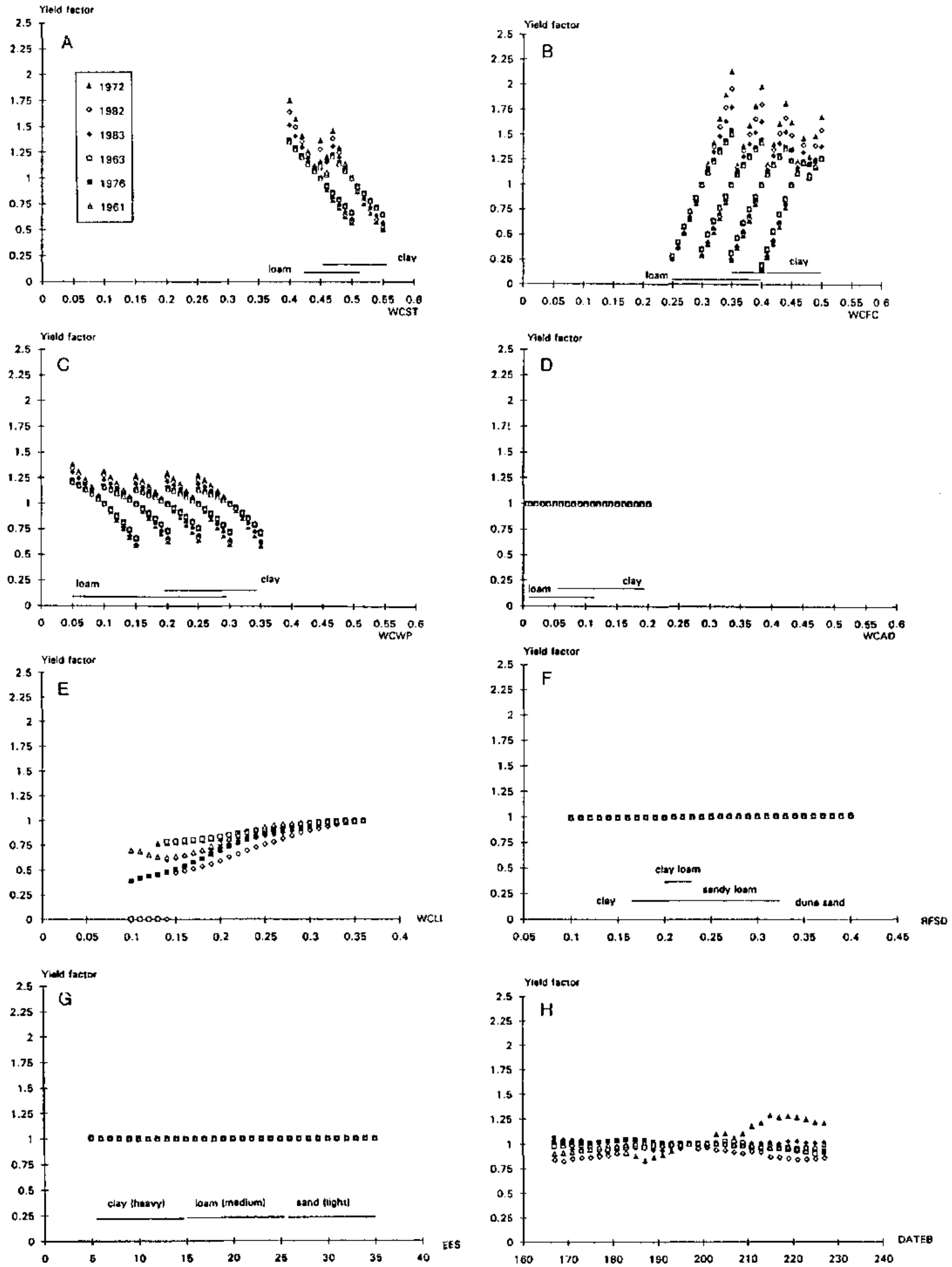

Figure 3. Simulated yield factor (see text) as function of WCST (A), WCFC (B), WCWP (C), WCAD (D), WCLI (E), RFSD (F), EES (G) and DATEB (H) for the three best and the three worst years between 1959 - 1984. The abbreviations of the parameters are explained in Table 1.

were no consistent differences between the best and the worst years. The yield factor remained between about 1.1 and 0.9 for five out of six years. In the worst year 1972, the yield factor increased to 1.3 when DATEB exceeded calendar day 216. The relatively small effect of DATEB on simulated yield may seem surprising, but is explained by the stable rainfall distribution during the growing season, combined with a good water holding capacity of the standard loam soil. Moreover, irradiation and temperature regimes are uniform, contributing to homogeneous growth conditions in time.

It should be noted that, while the sensitivities for the water content parameters were valid for all soil texture classes from sandy loam to clay, the sensitivities for the other soil parameters and for DATEB pertained to the standard loam soil only.

From the data presented in Figure 3, relationships were derived between the change in yield and the change in input parameter values. The 'relative yield change' was computed as the relative change in simulated yield per unit change in parameter value (in percentages):

$$\text{Relative change} = 100 \bullet (\mathrm{d}|Y| \,/\, Y) \,/\, \mathrm{d}P \qquad (5)$$

where

Y is the simulated yield at certain parameter value P,

$\mathrm{d}P$ the unit change in P, and

$\mathrm{d}Y$ the change in yield with $\mathrm{d}P$.

The unit parameter changes were: 0.01 volume fraction for WCST, WCFC, WCWP, WCAD and WCLI; 0.01 fraction for RFSD; 1 for EES; 0.01 m for WDCL; 1 day for DATEB. The relative yield change was fairly stable over all parameter-ranges, and average values were calculated. Table 3 lists average values together with extreme values for good years (standard yield > 3.5 t ha^{-1}), for average years and for bad years (standard yield < 2.5 t ha^{-1}). Simulated rainfed rice yield was extremely sensitive to the soil parameter WCFC, and very sensitive to WCST and WCWP. An inaccuracy of only 0.01 volume fraction in the determination of WCFC resulted in 12% inaccuracy in simulated rice yield in good and average years, and in 19% inaccuracy in bad years (see also section 'Summary and discussion).

The data in Table 3 can be helpful in setting up an efficient measurement strategy in the land-unit of our case study. There is no need to collect data on the soil parameters WCAD, RFSD, WDCL and EES (standard values suffice). Values for WCFC, WCST and WCWP, however, have to be collected with considerable accuracy. WCLI becomes an important parameter when at the start day of simulation the water content is 75% or less of field capacity. Because simulated rice yield was not very sensitive to DATEB, a general indication of sowing dates is sufficient.

Step 3: spatial yield probability

In Step 2, it was found that the water content parameters (except WCAD) had the largest impact on simulated crop yield, followed by initial water content and start day of simulation

Table 3. Average relative yield change (%) in simulated rice yield with unit change in soil and management parameters (see text).

	Good	Average	Bad
WCST	7.2	7.2	12.5
WCFC	12.0	12.0	19.0
WCWP	4.5	4.5	7.0
WCAD	0	0	0
WCLI1 (*)	1.7	1.7	1.7
WCLI2	2.9	2.9	2.9
RFSD	0	0	0
WDCL	0	0	0
EES	0	0	0
DATEB1 (**)	0.3	0.3	0.3
DATEB2	1.0	1.0	1.0

(*) WCLI1 is between 0.27 - 0.36; WCLI2 is between 0.15 - 0.27
(**) DATEB1: 5 out of 6 years; DATEB2: 1 out of 6 years

that had a minor (but still some) impact. Therefore, only these parameters were used in the calculation of spatial yield probability. The following probability distributions were used:
WCFC Because no precise information on the texture class of the soil unit was available, all loamy soil types had equal probability of occurrence. A uniform distribution of WCFC was constructed between the boundary values generally found for sandy loam and clayey loam (Figure 4A). Values for WCST and WCWP were calculated from WCFC using Equations 2 and 3.
WCLI As a standard, the water content of the soil at the start of simulation is taken to be at field capacity. However, in practice this will not be the case for all farmers. It was assumed that the number of farmers sowing at sub-optimal water contents decreases sharply with decreasing water content. A Beta distribution for WCLI as fraction of WCFC (FWCLI) was constructed (Figure 4B).
DATEB It was assumed that the pattern of sowing in the region followed a Normal distribution around the average (Figure 4C).

All other soil input parameters had the standard values for loamy soil.

Monte Carlo simulations were carried out, using N=500, for the three worst, for three average and for the three best years. The simulated yields were again normalized to the simulated standard yield. The resulting spatial yield probabilities are given as averages for bad, average and good years in Figures 5A and B. The spatial yield probability in bad and in average years was about the same, whereas that in good years was slightly different. In

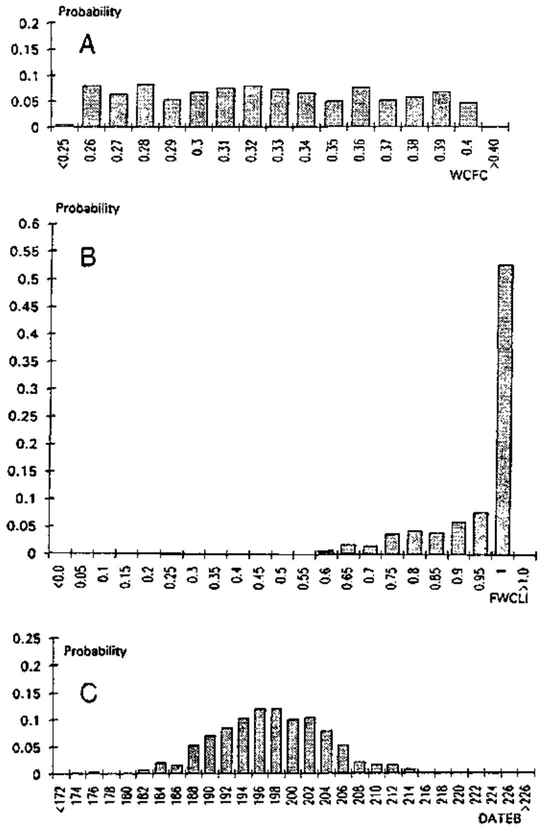

Figure 4. Probability distribution for WCFC (A), for WCLI (as fraction of WCFC; B) and for DATEB (C) used in Monte Carlo simulations to compute spatial yield probability.

bad and in average years, there was 80% probability that simulated rice yield was between 0.75 and 1.05 times the simulated standard yield. Any yield between 0.75 and 1.05 times the standard yield had about equal probability of occurrence. In good years, there was 75% probability that simulated rice yield was between 0.70 and 1.05 times the simulated standard yield.

The spatial yield probabilities of Figure 5 can be combined with the temporal probabilities of Figure 2 to give the overall-yield probability. For instance, the probability of a good yield of more than 3.5 t ha^{-1} in a given year is about 20% (Figure 2B). The spatial probability of Figure 5A, however, indicates that with the current uncertainty in soil parameters and in start day of simulation, there is still 75% probability that this yield varies between 2.5 and 3.7 t ha^{-1}.

Discussion

A framework of three steps was developed for crop yield simulation on a regional scale

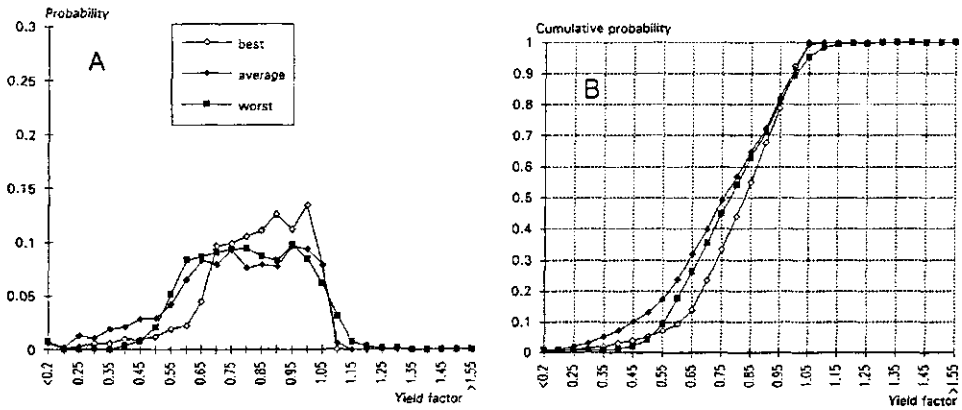

Figure 5. Spatial yield probability (A) and cumulative spatial yield probability (B) of predicted upland rice yield for bad, average and good years between 1959 - 1984, using input probability distributions as given in Figure 4.

which accounts for uncertainty in soil and management parameters. Sensitivity analysis (Step 2) was shown to be a useful tool to reveal the type of soil and management parameters that have a large impact on the simulation of crop yield. Rules of thumb can be derived for the accuracy with which these parameters need to be collected to satisfy a desired accuracy in predicted crop yield. Uncertainty in soil and management parameters, expressed in probability distributions is translated into spatial probabilities of simulated yield by using Monte Carlo techniques (Step 3). Probability distributions can be derived from expert knowledge, literature data or actual measurements. When sufficient measurements have been made to characterize the actual variability in the parameter values, then even the spatial *variability* of simulated rice yield can be calculated. In practice, a number of parameters will be 'uncertain' while others may be measured in detail. The resulting variation in simulated yield is therefore some mixture of probability and actual variability. The overall term spatial yield probability is preferred here to emphasize the existence of uncertainty in input parameter values.

The extreme sensitivity of simulated rice yield to the water holding characteristics of the soil, as found in this study, deserves special attention. Recent research suggests that rice is more tolerant to drought stress during vegetative growth than is currently modelled in MACROS (Wopereis & Kropff, personal communication 1992). As it is now in MACROS, stress effects on crop growth occur as soon as the water content of the soil drops below saturation. Therefore, rainfed rice growth may be less sensitive to the water holding characteristics of the soil than found in this case study.

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Agro-ecological zonation and extrapolation of field level research in Bangladesh: present status and future prospects

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Abstract

Good methods for extrapolation are essential for successful transfer of research findings and improved technologies from on-station and on-farm research sites to other and wider environments. This paper reviews the current methods of extrapolation that have so far been used in Bangladesh and discusses future prospects. Two methods have been used for macro- and meso-level extrapolation of rainfed rice cropping systems Aus - transplanted Aman: 1, land use mapping and manual map overlaying, and 2, the use of an Agro Ecological Zone (AEZ) computerized data base. For micro-level extrapolation, 'rules of thumbs' such as the use of topographic indices for water regime, varietal tagging and farmers' land typing were suggested. Crop modelling can be a useful tool in determining the potential productivities of crops and cropping sequences in different agro-ecological zones.

Introduction

Improved agricultural technologies are constantly being generated, tested and verified at on-station as well as on-farm research sites in developing countries. Any technology that seems to be appropriate or promising must be extended or extrapolated to larger target areas. Often, the lack of proper extrapolation methods has hampered the progress of technology dissemination for adoption. Therefore, establishing suitable methods for extrapolation of improved technologies from key research sites to target areas has become a major concern of researchers, extension workers and regional planners. At present, Bangladesh is heavily dependent on extensive field level verification trials, Multi Locational Trials (MLT) and land use mapping etc. Much work has also been done on agro-ecological zonation based on computerized data bases (FAO, 1988).

This paper reviews methods of extrapolation and the present status of extrapolation of research findings in Bangladesh. It also discusses future prospects of using crop modelling and GIS in extrapolation of research findings.

Extrapolation methods

Extrapolation in our context means the transfer of knowledge or farming technologies that are generated at a specific site (usually an experimental farm) to other and wider environments. Such 'target' environments are also termed 'recommendation domain' (see e.g. Garcia, 1993, this volume). Development of suitable methods for extrapolation of technologies from key research sites to target environments has become a major concern of planners, researchers and extension workers. Garrity suggests (as cited by Timsina, 1991) that environmental analysis of target areas for extrapolation may be carried out at four levels:

1. Mega level, referring to studies across countries where 'mega environments' are delineated at mapping scales of about 1:5 million;
2. Macro level, comprising studies at the level of an entire country, with a mapping scale 1:1 million,
3. Meso level, referring to studies at the regional level within a country, with a mapping scale of 1:100,000 to 1:250,000; and
4. Micro level, comprising studies that characterize the environmental variation among research sites, villages or village clusters, at mapping scales varying from 1:5,000 to 1:25,000.

Several methods are available to identify the extrapolation domains of transferable technologies at each level. Field researchers and extension workers need very simple and reliable methods. On the meso-level, Garrity et al. (1988) reported that land form classification can be used by researchers for research site stratification, and by (field level) extension workers for technology verification and extrapolation. For extrapolation of research findings to regional levels, Kropff et al. (1992) have distinguished two options:

- From data directly to mapping, such as agro-ecological zoning, soil mapping, land use mapping, area suitability mapping etc.
- From data via simulation modelling to mapping (hand drawn) or through combined use of GIS.

In both options, the availability and quality of data and suitable models are important issues. In the first option, regions are characterized by environmental variables (soil, land use, climate, hydrology) and subsequently classified as recommendation domain (target area) by similarities with Multi Location Trial (MLT) sites. This option has been applied in Bangladesh extensively (e.g. FAO, 1988): studies in which environmental variables were mapped and overlain manually, and studies in which data were analyzed and mapped with a computer and using GIS. The extrapolation methods of these studies will be illustrated below.

Present status of extrapolation of research findings

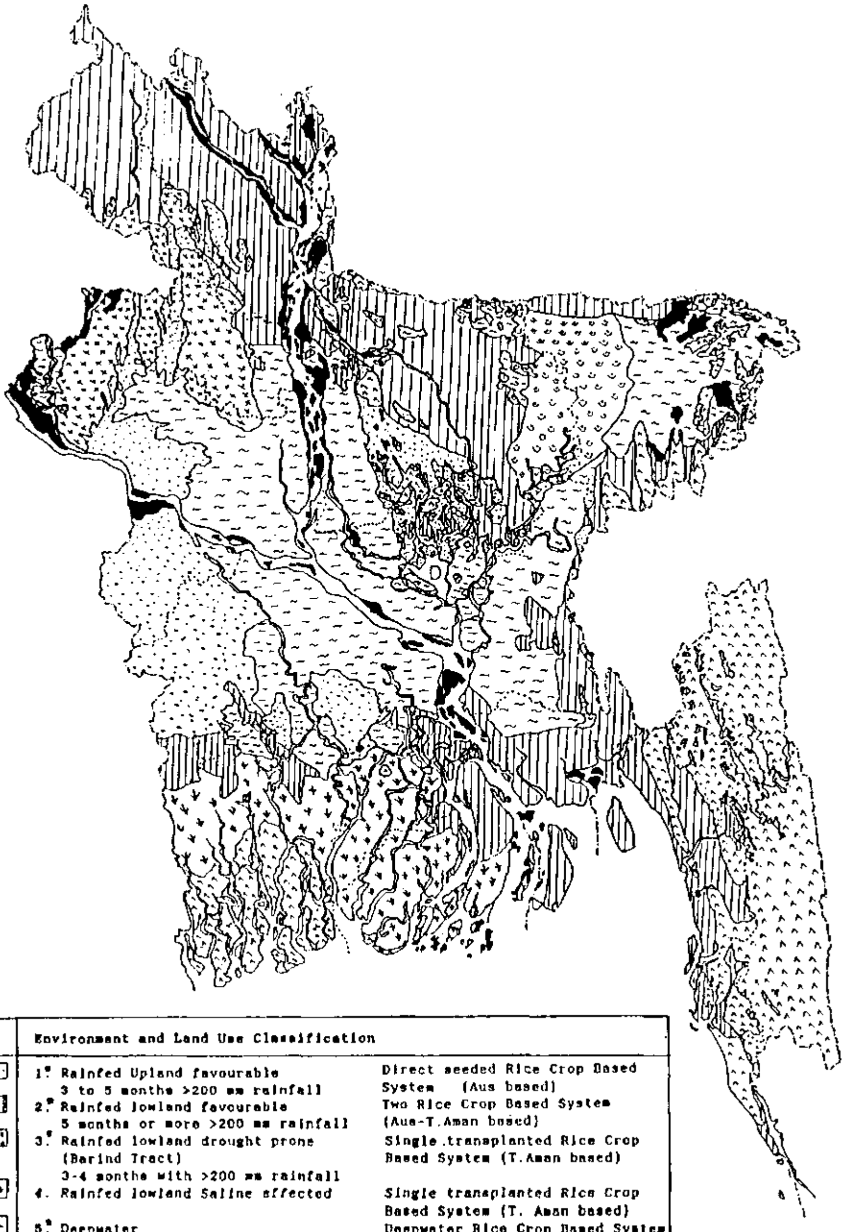
In Bangladesh different National Agricultural Research Centres (NARCs) have developed and conducted Cropping Systems Research (CSR) with Farming Systems Research (FSR) at 23 research sites. At most of these sites, improved cropping recommendations have been developed together with a package of component technologies that are now ready for extrapolation (Ahmed et al., 1990a, b). However, macro and micro-level delineation of the extrapolation areas are sometimes difficult or less effective due to lack of proper extrapolation methods and due to agro-ecological diversity within regions, subregions, and even within the lowest administrative units (i.e. 'thana' and village levels). Moreover, since many institutes are working on CSR sites even within a region, it is expected that there is an overlap of recommendations within any major agro-ecological region. To overcome the problems related to extrapolation, methodologies have been developed by the Bangladesh Rice Research Institute (BRRI) and the Bangladesh Agricultural Research Institute (BARI) (Ahmed et al., 1990a, b).

Extrapolation of BRRI's two rice crops systems on macro-level by manual map overlaying

The extension of BRRI's two rice crops system (Aus - modern Transplanted Aman) in the rainfed lowland environment is used as an example to illustrate the extrapolation principle (Ahmed et al., 1990a). The two crop rice system is a major system in Bangladesh and covers an estimated 3 million hectares of land (Figure 1). This system was developed in an area where soil is heavy textured and impermeable, with rainfall >200 mm per month for 5 months from May to September. The challenge of extensive Multi Location Trial researchers was to find out to what extent the newly developed Aus - modern T. Aman recommendation fitted in the existing Aus - T. Aman land use area. Choice of sites carefully followed the land use practices derived from district level land use maps, with follow-up field verification by BRRI and the Department of Agriculture Extension field personnel. The recommendation of rice variety combinations and the delineation of target areas was determined by the onset of the wet season, the onset of the cool season, soil texture, suitability for winter crops on residual moisture and by socio-economic factors. The environmental variables dictate the length of the growing season and the practicality of transplanting or direct seeding the Aus rice crop. The data used in this study were maps of environmental variables that were produced in a study conducted by the FAO (1988). Major target areas were identified by overlaying three important maps: the isoline map for the onset of nights with a minimum of 20 °C, the map showing the temporal boundaries of the cool season in the north-east and the north-west, and the isoline map for the onset of the April monsoon in the north-east. The three major target areas are the north-east (Target area 1), the north-west (Target area 2), and the central and south-east (Target area 3) (Figure 2). A summary of the recommendations for each target area is given in Table 1.

Quantification of target areas on macro-level by using computerized data bases

Initially, land use maps and climatic delimiters were used to transfer BRRI's MLT results (see above), but no effort was made to quantify areas for each thana (district). Such a quantification would be extremely useful for policy makers for production program



	Environment and Land Use Classification	
	1.* Rainfed Upland favourable 3 to 5 months >200 mm rainfall	Direct seeded Rice Crop Based System (Aus based)
	2.* Rainfed lowland favourable 5 months or more >200 mm rainfall	Two Rice Crop Based System (Aus-T.Aman based)
	3.* Rainfed lowland drought prone (Barind Tract) 3-4 months with >200 mm rainfall	Single transplanted Rice Crop Based System (T.Aman based)
	4. Rainfed lowland Saline affected	Single transplanted Rice Crop Based System (T. Aman based)
	5.* Deepwater	Deepwater Rice Crop Based System
	6. Bottom land deeply flooded	Winter rice crop only
	7. Reserve Forest and Hill Areas	Forest, Gardens, Orchards or Shifting Hill Cultivation
	8. New land (river and ocean) and seasonally flooded grasslands	Grassland

* (irrigated systems dispersed throughout these environments and cover 20-25 percent)

Figure 1. Environment and land use association in Bangladesh for rainfed systems (adapted and aggregated from SRDI Land Use Associations, 1972). Source: Naseem et al., 1987.

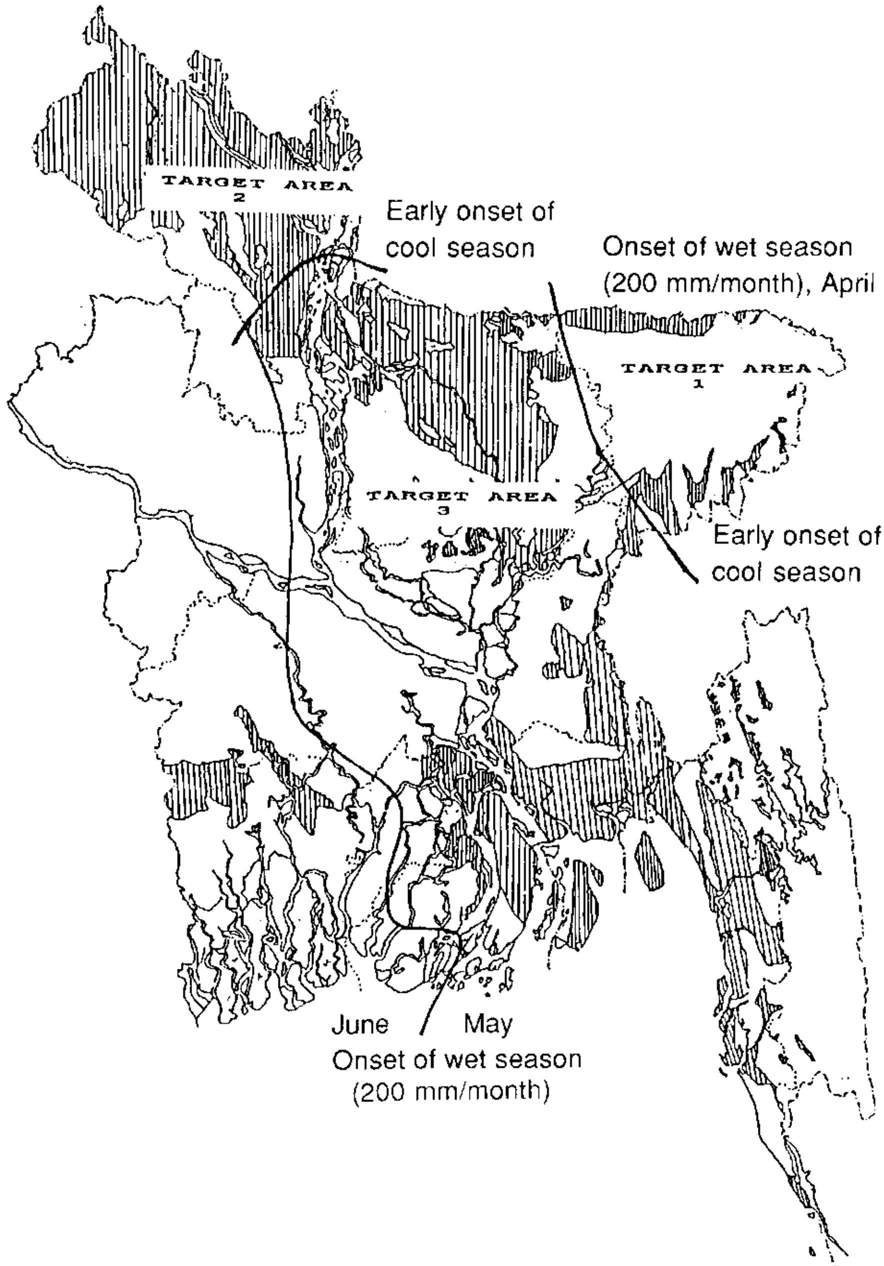


Figure 2. The major target areas for rainfed lowland two-rice cropping systems (Aus - transplanted Aman) in Bangladesh. Adapted and modified after Naseem et al., 1987.

Table 1. Rice varietal recommendations for the Aus - transplanted Aman cropping system in three major target areas in Bangladesh. For each target area, potential Upazilas* are given. It should be noted that if establishment is delayed due to drought or lack of ploughing animals, there are alternative strategies which include the use of a local variety. Source:: Naseem et al., 1987.

Target area 1: North-east	
Upazilas:	Jaintapur, Khadimpara, Gowainghat, Golapganj, Kamalganj, Kulaura
Rice variety	Comments
BR1 - BR11	Heavier textured, easily puddled soils with Aus transplanted
BR20 - BR11	Aus direct-seeded due to lack of labour and ploughs, and due to share-cropping arrangements
BR14 - BR11	Alternative option to BR1 - BR11 due to start of wet season in April. Aus transplanted by May 10 - 15.
Target area 2: North-west	
Upazilas:	Taraganj, Sayedpur, Lalmonirhat, Pirganj, Mithapukur
Rice variety	Comments
BR21 - BR11	First rice crop direct-seeded in March due to high moisture holding capacity of soil.
BR20 - BR11	BR11 transplanted by August 15.
BR21 - BR14	BR14 is harvested 10 - 14 days earlier than BR11
BR20 - BR14	Suitable where winter crop is sown after transplanted Aman.
Target area 2: Central and South-east	
Sub-unit 1:	Heavy textured impermeable soil with transplanted Aus
Upazilas:	Choddogram, Chagolnaiya, Dhagonbhuiyan, Mirsarai, Sitakunda, Fatikchari, Raozan, Joydebpur, Haluaghat
Rice variety	Comments
BR1 - BR11	Transplanting of Aus by May 25 and transplanting of Aman by August 30.
Subunit 2:	Light textured soil, slightly impermeable, with direct-seeded Aus.
Upazilas:	1 Barura, Nangal Court, Feni, Sonagazi, Sandwip, Jamalpur, Gouripur, Katiadi, Sreepur.
	2 Chodogram, Chagalnaiya, Sitakunda, Fatikchari, Haluaghat, Ishwarganj
Rice variety	Comments
BR21 - BR11	
BR20 - BR11	
BR21 - BR13	Aman is harvested early to enable timely
BR20 - BR14	establishment of early winter crops.

* Note: Upazila (or thana) is the most lower administrative unit in the country.

planning etc. The Agro-Ecological Zone (AEZ) data base, built in the FAO project (1988), contains data on soil, land type, hydrology and climate (temperature and rainfall) in computerized format. The environmental parameters used earlier for mapping only were now used to classify, delineate and quantify the area of land units on the basis of land type, inundation regime, length of wet season, length of cool season, and soil physical characteristics (soil permeability, available moisture holding capacity and soil consistency). The soil physical characteristics delimit areas for which the Aus rice may be direct seeded or transplanted and also the possibility of winter cropping on residual moisture. Table 2 gives the values of the parameters that were used to subdivide the three major target areas into recommendation zones for specific Aus - T. Aman cropping technologies. Table 3 quantifies, per district of the three major target areas, the areal extend of the land that is suitable for Aus - T. Aman rice cropping. The main recommended technology in the north-east was transplanted Aus - T. Aman - fallow, in the north-west direct seeded Aus - T. Aman - winter upland crop, and in the central and south-east a mixture of both.

The exercise of using the computerized AEZ data base for the extrapolation of recommendation domains showed that it complemented the use of land use maps. It was observed that land use maps can be used as a tool to identify MLT sites at the thana level. At the macro-level, the use of the computerized AEZ data base will also enable the synthesis of

Table 2. Criteria to classify and delineate areas that are suitable for recommendation of rice cropping systems based on Aus - transplanted Aman. Source: Ahmed et al., 1990a.

A Broadly delimiting Aus - transplanted Aman land

High and medium high land (up to 30 cm inundation) with slope < 3%.

B Delimiting major target areas by rainfall and temperature regime

Target area 1	Rainfall	More than 6 wet months;
	Temperature	'Early cool season'
Target area 2	Rainfall	5 wet months
	Temperature	Nights less than 20 °C before Nov. 1
Target area 3	Rainfall	5 wet months
	Temperature	Nights less than 20 °C after Nov. 1

C Delimiting land units within the major target areas

1 Land suitable for direct seeded Aus - transplanted Aman - winter crop
Available soil moisture > 200 mm; topsoil consistence friable; moderate soil permeability

2 Land suitable for transplanted Aus - transplanted Aman - winter crop
Available soil moisture < 200 mm; topsoil consistence friable to firm; slow to moderate soil permeability.

Table 3. Acreage of land that is suitable for rainfed Aus - transplanted Aman cropping recommendation per district of each major target area. Source: Ahmed et al., 1990a.

Target area 1: North-east	
Sylhet	32355
Moulvibazar	62053
Habiganj	31407
Sherpur (partly)	46612
	172427
Districts with 10000 - 20000 ha suitable land: Sunamganj	
Target area 2: North-west	
Nilphamari	28587
Rangpur	73266
Lalmonirhat	38585
Kurigram	40309
Gaibandha	29957
	210704
Districts with 10000 - 20000 ha suitable land: Panchagarh	
Target area 3: Central and South-east	
Mymensingh	54488
Tangail	34596
Gazipur	21009
Chittagong	31307
Bhola	45599
Faridpur	29744
	216743
Districts with 10000 - 20000 ha suitable land: Sariatpur, Jamalpur, Netrokona, Dhaka, Kishorganj, Bandarhan, Barisal, Narsingdi, Patuakhali.	

recommendations made by different NARCs (Ahmed et al., 1990a). The limitation of the current AEZ data base is that it does not include the recent irrigation developments or embankments. The AEZ data base is based on reconnaissance soil survey data of the early 1980s.

Micro level extrapolation

At BRRI, attempts were also made to develop methods for micro level extrapolation of Farming Systems Research technologies (Ahmed et al., 1990a). It is not possible to develop land use maps on the village or union-scale from the AEZ data base, as the latter is based on a reconnaissance survey only. The issue of addressing micro level variation is raised by Garrity et al. (1988) for delineation of land units at the land facet level. Recently, the Rice Farming Systems Division (RFSD) of BRRI started to develop a low-cost technique for the use of agro-ecosystem mapping (hand drawn) as a simple tool for micro-level delineation of extrapolation areas at a village in the Sitakunda and Kamalganj thanas (Ahmed et al., personal communication). 'Rules of thumb' such as the use of a topographic index for water regime, varietal tagging and farmer land typing were suggested. Agro-ecosystem mapping involves the making of social, enterprise, topography and hydrology maps and transects of agro-ecological zones (Lightfoot et al., 1989).

Prospects of using simulation modelling in extrapolation of recommendation domains

The use of crop growth simulation models as tools for yield prediction and extrapolation has been demonstrated by different authors for rice (Herrera-Reyes & Penning de Vries, 1989; Dua et al., 1990), wheat (Aggarwal & Penning de Vries, 1989), soybean (Penning de Vries et al., 1992) and cowpea (Timsina, 1991). Once appropriate crop and environmental characteristics are available for each particular situation, and the model is validated using results from independent experiments, the models can be used to predict the yield of different annual crops. The experience of crop modelling at BRRI is presented for a case-study on the zonation of rice-wheat cropping by Sattar (1993, this volume). The combined use of crop modelling and Geographic Information Systems, such as the AEZ data base described above, has been demonstrated by Wopereis et al. (1993; this volume) and Pannangpetch (1993, this volume). Crop modelling and simulation can directly serve as an input in the decision making process or it can be input into the GIS data base. Results of simulation studies and crop modelling can best be communicated to the end-user when its output is presented in spatial entities. It is in this respect that GIS will be very helpful (Godilano & Carangal, 1990). Based on BRRI's experience, some prerequisites for the successful use of GIS and simulation modelling in the extrapolation of recommendation domains are:

- Availability of good quality data on weather, crops, soil, etc.,
- Availability and low cost of GIS software,
- Availability of skilled man power for modelling and GIS, and
- Availability of long term weather data required for simulation modelling.

The effectiveness of GIS and crop growth modelling depends on the accuracy and timeliness of the input data and upon the renewal of information. Remote sensing could offer the potential to meet these criteria.

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Crop growth modelling as a tool to determine potential irrigated area for rice-wheat cropping in Bangladesh

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Abstract

The crop growth models AMAN and MACROS (module L1D) were used to determine potential production of Aman rice and wheat, respectively, in different regions covering broad thermal zones of Bangladesh. The potential rice yield varied with transplanting date and location. Photoperiod sensitive local varieties gave good yield (4 - 5 t ha^{-1}) when planted in mid-August, while the modern varieties gave good yield when planted between mid-July to mid-August. The photoperiod insensitive variety gave good yield up to mid-August transplanting in the cool northern regions. In the warmer southern regions rice yield did not exceed 3 - 4 t ha^{-1}.

The potential wheat yield varied from about 1.2 to 7 t ha^{-1} depending on sowing date, location and variety. Wheat thrives best in north and north-western regions of the country if planted in November. In the mid-western region yield ranged from 3.4 to 5.9 t ha^{-1}.

The cut-off date for transplanting rice and sowing wheat has also been determined.

Introduction

Rice is the main staple food crop of Bangladesh grown in about 10 million hectares. Its production and yield increased linearly from 1951 to 1975 and exponentially thereafter. There was a slow growth of rice area during the above period (IRRI, 1991). This increase in rice production, however, can not keep pace with the increasing growth of population, and a perennial crisis of food exists in Bangladesh. Among the four rice crops, the wet season second (July to December) rice crop (Aman rice) is grown in about 40% of the rice area in Bangladesh.

Until the early 1970s, wheat was considered to be a poor man's food and was mostly grown by marginal and subsistence level farmers. However, among the principal cereal imports since the early 1970s, wheat takes first place because of the increased demand for wheat due to government publicity, wheat bias in food ration system, wheat channeled into rural diet by food-for-works program and general acceptance in food habit (Ahmed & Elias, 1986).

Nowadays, wheat has been established as the second major cereal crop of Bangladesh and accounts for about 9% of the total cereal production (Kibria, 1986). The area under wheat in the country increased from 0.12 m ha in 1972 - 1973 to 0.53 m ha in 1981 - 1982. After 1982, the area, production and yield of wheat reached a plateau. Modern varieties and associated cultural practices became available during the mid 1980s (Razzaque et al., 1986) but neither the area nor farm level production could be improved further because of several socio-economic and physical factors (Ahmed & Elias, 1986).

Wheat is grown in the dry season (November to March), usually after the harvest of the previous Aman rice, in competition with other crops such as dry season rice (Boro rice). Higher water requirements for growing Boro rice relative to wheat (7.4 times more irrigation cost for Boro rice than for wheat (Harun-ur-Rashid & Islam, 1986)) could not encourage farmers to grow wheat. Among the physical factors, the climate is responsible for high instability of wheat yield. This is because the sowing of wheat may get delayed due to either the late planting of Aman rice, or to the use of long duration Aman cultivars. This increases the risk of exposing wheat crop to adverse (high) temperature during the grain filling stage which reduces grain yield (Maniruzzaman, 1986). National rice and wheat breeders are trying to develop early maturing rice varieties and wheat varieties that are tolerant to high temperatures at the reproductive and ripening stages.

Therefore, the productivity of transplanted Aman rice and wheat in a rice-wheat rotation is much dependent on timely establishment of the crops and availability of water in a particular agro-ecological zone (Figure 1). This research work, if carried out experimentally, generally costs a lot of money and takes a lot of time. Aggarwal & Penning de Vries (1989) and Aggarwal (1991) used simulation models to delineate wheat production areas in various agro-climates of south-east Asia. Simulation models could be a useful tool to assess the potential production of crops, and to select suitable variety combinations. Also, simulation modelling can be used to determine the cut off date for sowing wheat and transplanting rice in each of the agro-ecological zones (AEZ's) of the country, spending little time and money. In this paper simulation models are used to:

1 Determine the potential production of rice and wheat in transplanted Aman rice - wheat cropping pattern under irrigated conditions;
2 Establish the cut-off dates for transplanting rice and sowing wheat; and
3 Indicate areas having potential of rice-wheat crop rotation in the 30 agro-ecological regions of Bangladesh.

Material and methods

The potential production of one photoperiod insensitive (cultivar BR14) and three photoperiod sensitive *rice* varieties (weakly sensitive cv. BR11 and strongly sensitive modern cv. BR22, and the most popular local improved cv. Nizersail) was estimated using a simulation model, AMAN. The basic structure of the model is based on the MACROS module L1Q, coupled with the tillering sub-module TIL of Penning de Vries et al. (1989). Unlike in

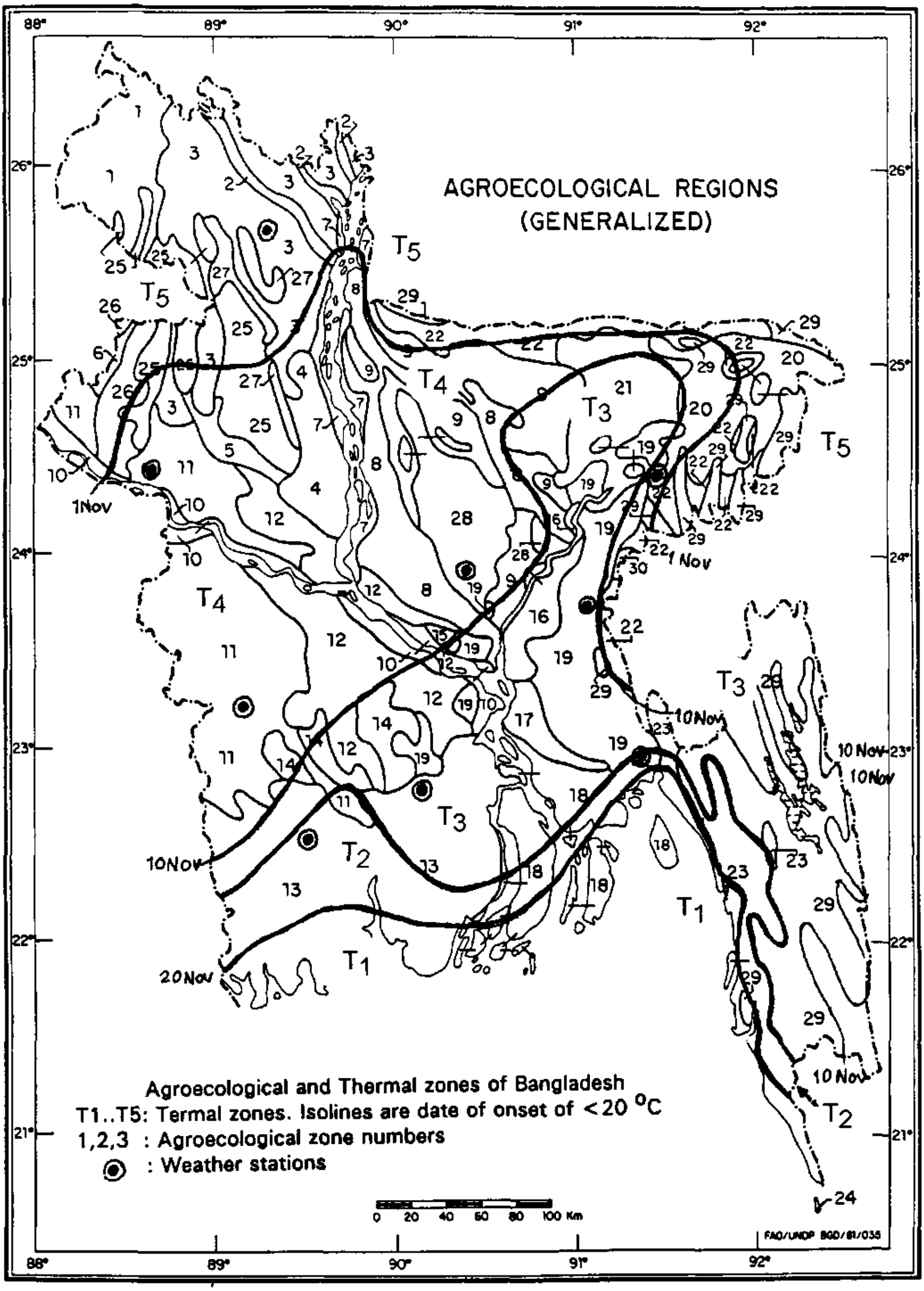

Figure 1. Agro-ecological and thermal zones of Bangladesh. Source: FAO/UNDP, 1988.

module L1Q, as described earlier (Sattar & Roy, 1991), this model simulates plant growth starting from germination in the seedbed. On the day of transplanting, all the plant dry masses are reduced by a density reduction factor and the phenological development is set back. Floral initiation does not take place until the crop is exposed to, depending on the cultivar (variation in the degree of sensitivity to photoperiod), 10 to 12 hour daylength. The critical temperatures for exertion of panicle and spikelet fertility has been set at 18 and 16 °C, respectively, for all the test cultivars except for cv. BR11. The model was well validated for the varieties except for cv. BR11 (Sattar & Roy, 1991); the latter has a very weak tolerance to low temperature and has to be validated for temperature tolerance.

For estimation of *wheat* yield, the MACROS module L1D was used with crop data for an Israeli spring wheat variety (Arminda) obtained from the data base of Penning de Vries et al. (1989). The model was validated with data collected from two experiments conducted by the author at the Wheat Research Center of the Bangladesh Agricultural Research Institute during 1990 and 1991. The two most popular varieties of wheat, Kanchan and Sonalika, were used; the latter matures about a week earlier. The model was validated well for shoot and leaf dry weights but not for stem dry weight (Figure 2).

The potential production, i.e. with ample supply of water and nutrients; no pests and diseases, of rice and wheat were simulated for eight locations (that had at least 3 years complete measured daily weather data between 1980 - 1990 for maximum and minimum air temperature, solar radiation or sunshine hours, rainfall and relative humidity) covering the 30 major agro-ecological zones of Bangladesh (AEZ, Figure 1). The reader is referred to FAO/UNDP (1988) for a description of the AEZ's.

Sixteen combinations of the above described four rice varieties with four transplanting dates (15th of July, August, September and October), and eight combinations of the two wheat varieties with four sowing dates (November 15, December 1 and 19, and January 4) were simulated. The seedling age of rice at transplanting was 30 days.

Results

Rice yield

The potential yields varied with planting date. In all locations, modern varieties, except cv. BR11, produced the highest grain yield when transplanted between mid-July to mid-August while the local improved varieties and BR11 produced the highest grain yields when transplanted in mid-August (Table 1). Photoperiod sensitive varieties flowered, irrespective of transplanting dates, in mid-November and yielded best (4 - 5 t ha^{-1}) in north-western regions where the cool climate sets in during the grain filling stage. The larger fluctuation of diurnal air temperatures in these areas favoured better grain filling (unpublished result of the author). On the other hand, the flowering time of the photoperiod insensitive variety varied with transplanting date and gave higher yields with transplanting up to mid-August. In the warmer regions (south and south-eastern), grain yield did not exceed 3 - 4 t ha^{-1}. This indicates that the agro-climate of north and north-western regions is more favourable to

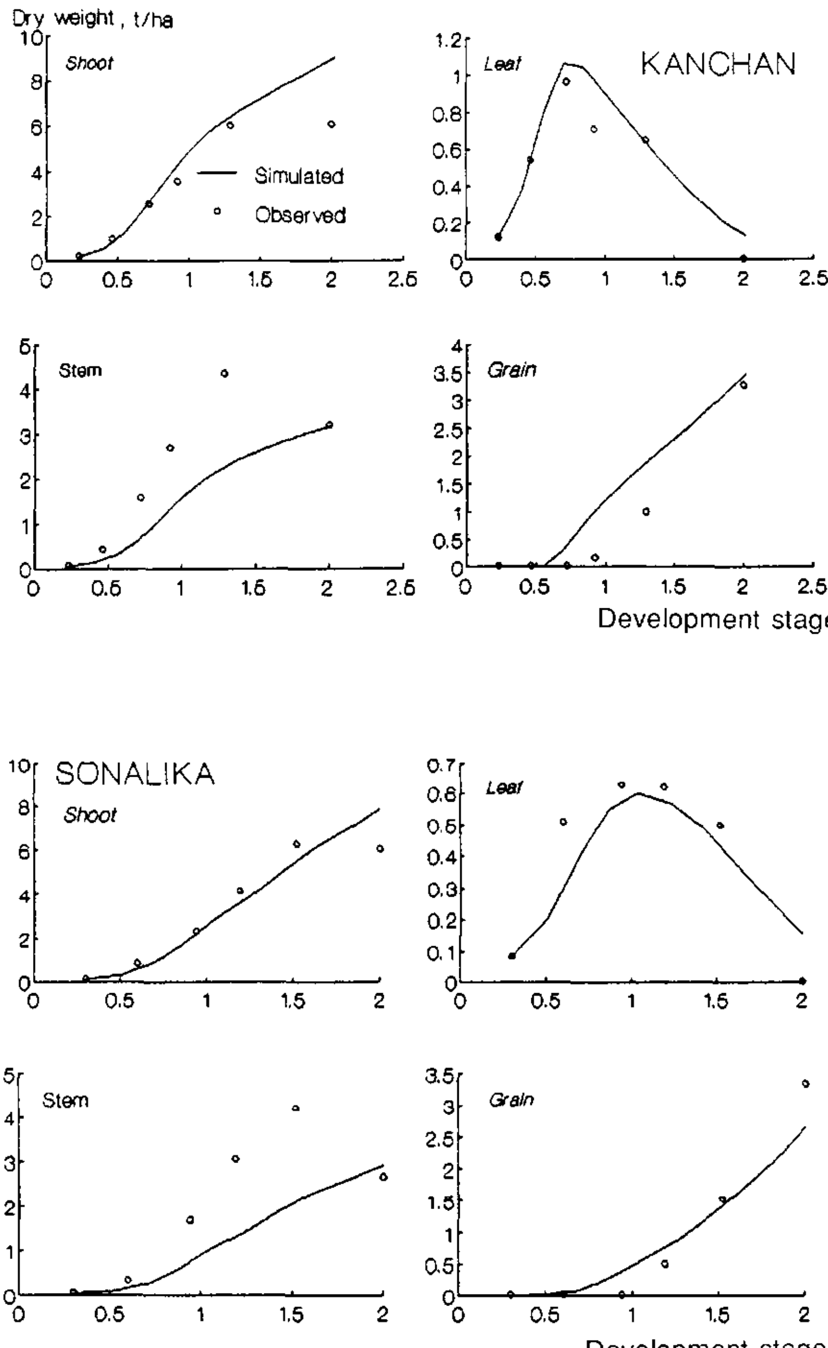

Figure 2. Simulated (solid lines) and observed dry weights of shoot, leaf, stem and grain ($t\ ha^{-1}$) of two wheat varieties Kanchan and Sonalika. Sowing date was 15 November 1991, in Joydebpur. Development stage 0 is at emergence, 1 at flowering and 2 is maturity.

Table 1. Average simulated grain yield of rice by variety and transplanting dates in different agro-ecological zones (T1, T2 etc. are Thermal zones; 1, 2, etc. are AEZ numbers as in Figure 1).

Variety	Yield ($t\ ha^{-1}$)	Transplanting dates July 15	August 15	September 15	October 15
Nizersail	4 - 5		T3/13,18 T4/11	T2/18,19,23	
	3 - 4	T3/13,18 T4/10-11,28	T2/18,19 T4/10-11,28 T5/1-3	T3/13	
	2 - 3	T2/18 T3/16,17,19 T5/1-3	T3/16,17,19	T4/10-11,28	
	1 - 2			T3/16-19 T5/1-3	
	< 1				All
BR22	4 - 5	T3/13 T4/11	T3/16-19 T4/10,28	T3/13, 16-19	
	3 - 4	T2/18,19 T3/16-19 T4/10-11,28 T5/1-3	T2/18-19 T5/1-3	T4/11, 28 T5/1-3	
	2 - 3			T4/10	
	1- 2			T2/18,19	T4/28
	< 1				All
BR14	4 - 5	T3/16-19 T5/1-3	T4/11,28 T5/1-3		
	3 - 4	T2/18-19 T4/10-11,28	T2/18-19 T3/13 T4/10,16-19	T2/18-19 T3/13 T4/11,28 T5/1-3	
	2 - 3	T3/13		T3/16-19 T4/10	
	< 1				All
BR11	4 - 5		T4/10-11,28 T3/13	T2/16-19	
	3 - 4	T3/10-11,28 T4/13,18,19,23 T5/1-3	T3/16-19 T4/13,18,19,23 T5/1-3	T3/13,19 T4/10-11 T5/1-3	
	2 - 3	T3/16-19		T4/10-11	
	1 - 2				T2/18,19 T3/19,23
	< 1				All

Table 2. Average variation in simulated rice yield (t ha^{-1}) at two locations in Bangladesh.

Variety	Trans-planting date	Joydebpur				Rajshahi			
		Min. yield	Max. yield	Mean yield	St.d.	Min. yield	Max. yield	Mean yield	St.d.
N.sail	July 15	2.8	3.6	3.4	0.32	2.9	3.2	3.1	0.16
	Aug 15	3.5	4.2	3.9	0.28	2.3	4.2	3.2	0.77
	Sept 15	1.9	3.2	2.6	0.54	0.3	3.3	1.9	1.25
	Oct 15	0.0	0.7	0.3	0.27	0.0	0.0	0.0	0.00
BR22	July 15	3.2	4.2	3.9	0.39	3.4	4.1	3.7	0.30
	Aug 15	4.2	4.7	4.5	0.18	3.9	4.7	4.2	0.37
	Sept 15	3.3	3.9	3.7	0.27	0.4	4.1	2.5	1.54
	Oct 15	0.0	0.9	0.6	0.39	0.0	0.1	0.05	0.07
BR11	July 15	3.3	3.7	3.5	0.17	3.6	4.1	3.8	0.23
	Aug 15	3.6	4.5	4.2	0.32	3.7	4.1	3.9	0.18
	Sept 15	3.2	3.9	3.6	0.28	0.9	3.9	2.6	1.27
	Oct 15	0.0	0.8	0.5	0.34	0.0	0.3	0.1	1.35
BR14	July 15	3.0	3.9	3.5	0.38	3.1	3.7	0.3	0.25
	Aug 15	4.0	4.2	4.1	0.09	4.0	4.2	4.1	0.08
	Sept 15	2.7	3.3	3.1	0.22	0.8	3.3	2.1	1.05
	Oct 15	0.0	0.6	0.3	0.26	0.0	0.0	0.0	0.0

produce yields > 4 t ha^{-1}, while that of the southern and eastern zones do not allow yield potentials to exceed 3 - 4 t ha^{-1}. In other words, the potential yields increased with increase of latitude and elevation (elevation of the country varies from 3 meter above sea level in the south to 19 meter in the north).

The data in Table 1 and Figure 1 show that in regions where low temperatures set in early (north and north-western) rice should be transplanted between July and mid-August; further delay will reduce yield drastically. Rice yield fluctuated much when transplanted late, particularly in cooler regions because of annual variations in weather, namely air temperature, as is evidenced from the high standard deviation (Table 2). In the warmer, southern regions, rice yield was relatively stable with variation in transplanting date.

Wheat yield

Potential yields varied from about 1.2 to 7 t ha^{-1} depending on sowing date, location and variety (Table 3). Prolonged low temperatures during the reproductive stage increased wheat yield in general. Therefore, wheat thrived best in the north and north-western regions of the country (Thermal zone T5) where grain yields of 5 to 7 t ha^{-1} are possible if sown in November. In the mid-western region of the thermal zones T3 - T4, wheat yields ranged from 3.4 to 5.9 t ha^{-1} when sown in optimum time (mid-November to mid-December).

Table 3. Average simulated wheat yields by variety and sowing dates in different agro-ecological zones (T1.. : Thermal zones; 1,2, ...: AEZ's; as in Figure 1).

Variety	Yield ($t\ ha^{-1}$)	Sowing dates			
		November 15	December 1	December 19	January 4
Sonalika	5 - 6	T5/1-3,11,25,26			
	4 - 5	T4/10-12,28	T5/1-3	T5/1-3	
	3 - 4	T3/11-14 T4/11	T4/10		
	2 - 3			T4/11,28	T5/1-3
	1 - 2				T4/10-13
Kanchan	6 - 7	T4/10,11 T5/1-3			
	5 - 6	T4/11-13,28	T4/10,11	T5/1-3	
	4 - 5		T4/11-13		T5/1-3
	3 - 4			T4/10,11,28	
	2 - 3			T2/13	T4/10-13

The data in Table 3 show that the variety Kanchan has a higher yield potential than Sonalika. Also for good yields, wheat should be sown in November and not later than the first week of December irrespective of the location. It is also evident that when sowing is delayed until mid-December, Kanchan still yields better than Sonalika.

Cut-off dates of sowing wheat

In a rice-wheat cropping system the harvest date of the first crop (rice) determines the sowing of the second crop (wheat). The maturity dates of rice varied with variety as well as with locations. A variety takes a little longer to mature in cooler regions. It appears from Figure 3 that when rice is transplanted around mid-August (the optimum date of transplanting rice) wheat can be sown around December 20 at three out of eight locations after cv. Nizersail, the longest duration rice variety; around December 15 at 5 locations after cv. BR22, and around December 15 at all locations after cvs BR14 and BR11.

Conclusions

The potential production of rice varied from 4 - 5 $t\ ha^{-1}$ when transplanted up to mid-August. Photoperiod sensitive local varieties performed better when transplanted in mid-August, whereas the modern varieties did well even with early transplanting. North and north-western zones have higher rice yield potential than the rest of the country. Likewise, when sown at the optimum time (November) the yield potential of wheat varied, depending

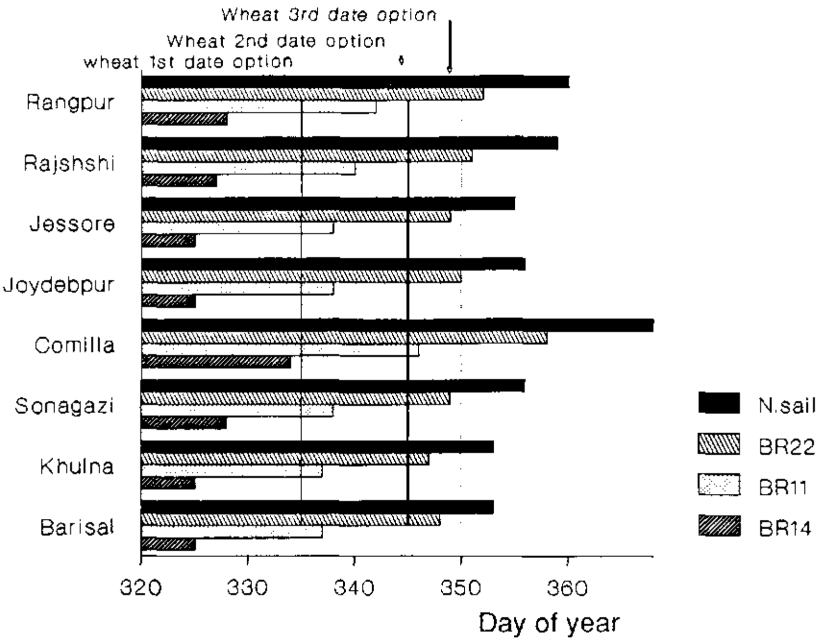

Figure 3. Dates of maturity of rice transplanted on 15 August (Day of year 228).

on variety and location, from 3 - 7 t ha^{-1}. North and north-western regions of the country had higher yield potential than the other parts of the country. The wheat variety Kanchan had higher yield potential than Sonalika and gave higher yield with late sowing.

Crop growth simulation models could estimate yield potential in various agro-climatic regions satisfactorily. Therefore, it appeared to be an effective tool to indicate potential areas for rice and wheat when grown in different agro-climatic zones. This approach will be useful for agro-climatic zonation of Bangladesh.

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The use of simulation and systems analysis in rice agro-ecology in Indonesia

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Abstract
Crop growth modelling and systems analysis were applied as tools in the agro-ecological characterization of rice production in Indonesia. The module L1D of the MACROS rice growth model was used to compute potential rice yield as function of transplanting date for seven selected agro-ecological environments on Java, Sumatra, Kalimantan, Sulawesi and Flores. The pattern of predicted potential rice yield with transplanting date varied between the agro-ecological sites and was generally related to the pattern of solar radiation as determined by cloudiness. At Bogor, on Java, highest simulated rice yields obtained with transplanting in May - June were associated with high risk, whereas low simulated yields obtained with transplanting in December - January were associated with low risk. The yield gap between actual rice yield and simulated potential rice yield was lowest on Java and highest on the so-called outer-islands.

Introduction

Sustaining rice self sufficiency and food security are the most important agricultural policy issues in Indonesia. Theoretically, this condition could be reached if the increasing rate of rice production is equal to or higher than the growing demand. However, recently the rice production increase was reported to start leveling off. Therefore, new ways to increase rice production need to be found (Manwan & Adinyana, 1990).

Three options have been identified for increasing rice production:

1 Increasing rice production areas, which includes expansion of rice areas into new land such as swampy areas, or new lowland rice fields and/or with increasing rice cropping intensity;
2 Increasing productivity, which also includes adoption of improved technologies (better varieties, fertilizer management, water management; better transplanting time, etc.);
3 Improving pre and post harvest technology to reduce yield loss due to inappropriate methods of harvesting, handling, transporting, and storing the products (Pusat Penelitian dan Pengembangan Tanaman Pangan, 1991).

The agricultural areas in Indonesia vary in their environment (climate, soil, physiography and other biophysical factors) (Las et al., 1991). Therefore, sites need first to be properly characterized, then evaluated for their development potential according to the three options mentioned above. The final development policy should also consider their suitability in terms of social, economic and environmental aspects. The next step, zoning the areas based on their biophysics or agro-ecology becomes very important. It will allow the adoption of the most suitable technology package on an operational scale and to transfer it to other similar agro-ecological regions.

In the above scheme, systems analysis and simulation can play an important role e.g. in predicting potential yields, selecting the best transplanting dates, choosing the best rice varieties, analysing the yield-limiting factors, risk analysis under present conditions or under different cropping systems scenarios, and also to characterize and to delineate agro-ecological environments.

The objectives of this study are to identify rice yield potentials at different agro-ecological sites in Indonesia, to analyse the rice yield-limiting factors, and to interpret the difference between the potential yields and the actual yields (yield-gap analysis).

Material and methods

Seven locations were selected from the main islands of Indonesia, namely Java (2 sites), Sumatra (1 site), Kalimantan (2 sites), Sulawesi (1 site), and Flores island in the east Nusa Tenggara province (1 site) (Table 1). The sites are different in their climates, soils, elevation, and agriculture management practices, and they represent specific rice agro-ecological areas on the respective islands.

For each location, the potential rice yield was simulated using the model MACROS module L1D (Penning de Vries et al., 1989). Potential yield means that the crop is grown

Table 1. Agro-ecological characteristics of the 7 sites used in the study of rice agro-ecology. Soil orders are given according to the FAO classification (m asl = meters above sea level).

No.	Location	Province	Elevation (m asl)	Soil order	Climate
1	Muara/Bogor	West Java	260	Latosol	Wet
2	Genteng	East Java	17	Regosol	Medium
3	Sukarami	West Sumatra	928	Andosol	Wet
4	Pontianak	West Kalimantan	2	Alluvial	Medium
5	Palangkaraya	Central Kalimantan	12	Podzolic	Medium
6	Lanrang	South Sulawesi	25	Mediteran	Dry
7	Maumere	East Nusa Tenggara	3	Regosol	Very dry

under optimum supply of water and nutrients, and without pest and disease infestation. Weather data (i.e. daily minimum and maximum temperature and solar radiation) of 10 - 19 years were averaged and used in this simulation, except for the Muara/Bogor site (for which weather data of 1981, 1982, 1983 and 1985 were used), Lanrang (1981 and 1985), and Sukarami (1981 and 1983). Twelve different days of transplanting (DATEB, day of year) were used: 1, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300 and 330. Crop characteristics of rice variety IR64 were used in the simulations (Penning de Vries et al., 1989).

A more detailed study of the effects of weather on rice yield potential was done for the Muara/Bogor site, as an example of a method for analysing rice yield-limiting factors and of risk analysis. In the risk analysis study, the yield potentials of the different years and transplanting dates were simulated separately. In the analysis of yield-limiting factors, rice yield potentials were simulated for two transplanting dates, day 150 (30 May 1982) and day 300 (27 October 1982), and using actual weather data and four fictive scenarios of climatic conditions, namely:

1 The maximum temperatures during the rice growth for the late May planting (DATEB = 150) (TMAX1) were replaced with the ones for the late October planting (DATEB = 300) (TMAX2), while the other variables were kept as the original;
2 The minimum temperatures during the crop growth for the late May planting (DATEB = 150) (TMIN1) were replaced with the ones for the late October planting (DATEB = 300) (TMIN2);
3 The solar radiation during the rice growth of the late May planting (DATEB = 150) (RAD1) were also replaced with the ones for the late October planting (DATEB = 300) (RAD2); and
4 The weather data of 36 days before harvest of the late October planting (DATEB = 300) were replaced with the ones of the late May planting (DATEB = 150).

The statistical data of the actual rice yields at the district (Kabupaten) level of Indonesia were gathered for the years 1987, 1988, 1989 and 1990 (Biro Pusat Statistik, 1987; 1988; 1989; and 1990). These data were considered as the actual yield levels of the sites, and used in the 'yield-gap' analysis.

Results and discussion

According to the average 10 - 19 years of weather data, the seven sites selected in this study varied in their climatic variables, mainly average total yearly rainfall, average daily solar radiation and average daily air temperatures (Table 2).

Potential yields all sites

The pattern of potential yield as function of transplanting date was different for the seven rice agro-ecosystems (Figures 1 and 2, selected sites). The yield stability within a year, i.e.

Table 2. The values of some climatic variables of each site based on the average of 10 - 19 years weather data.

Location	Radiation (ly d^{-1})	Rainfall (mm y^{-1})	Daily temperature (°C) Maximum	Minimum	Mean
Muara/Bogor	340	3985	30.2	21.5	25.4
Genteng	463	2208	30.4	21.0	26.4
Sukarami	368	2740	24.4	18.3	21.2
Pontianak	469	3482	32.1	22.7	27.3
Palangkaraya	474	3180	32.2	23.0	27.5
Lanrang	475	2180	31.0	23.3	27.4
Maumere	530	1126	31.8	23.4	27.9

with different transplanting dates, was higher for the drier environments, such as Lanrang (Figure 1E) and Maumere (Figure 1F), than for the wet ones (Bogor (Figure 2) and Sukarami (Figure 1B)). In wet climate zones, the cloudiness varies distinctly within a year which affects the solar radiation. In the dry climate zones, rainfall is low and the cloudiness variation within a year is also less.

In the medium wet zones the pattern of yield potential with transplanting date was sometimes similar to the wet zones, such as in Pontianak (Figure 1C) and Genteng (Figure 1A), and sometimes similar to the dry zones, such as in Palangkaraya (Figure 1D). Therefore, we found that each agro-ecological environment had different patterns of yield potential.

The pattern of rice yield potential within a year of most sites was inversely related with the pattern of rainfall, namely: high yields in dry seasons (low rainfall) and low yields in wet seasons (high rainfall). This is due to low solar radiation during the wet season and high solar radiation during the dry season. A rainy season usually occurs during October - April, except for Maumere and Palangkaraya. In Maumere, rainfall is very low and mostly occurs during December - January. However, the lowest yield potential occurs in July - August when the solar radiation reaches its minimum. In contrast, in Palangkaraya the rainfall does not affect solar radiation or yield potential very much. This is because more than 60% of the rains fall in the evening. Therefore, solar radiation levels during the day are still high.

Potential yield analysis Bogor site

The pattern of rice yield potential as function of transplanting date varied between years (Figure 2). Transplanting rice between the end of January (day of year 30) and the end of June (day 180) resulted in relatively large differences between the years (high risk). Transplanting between the end of December (day 360) and the first of January (day 1) resulted in the most stable yields (low risk). Thus, although transplanting between the end of May (day

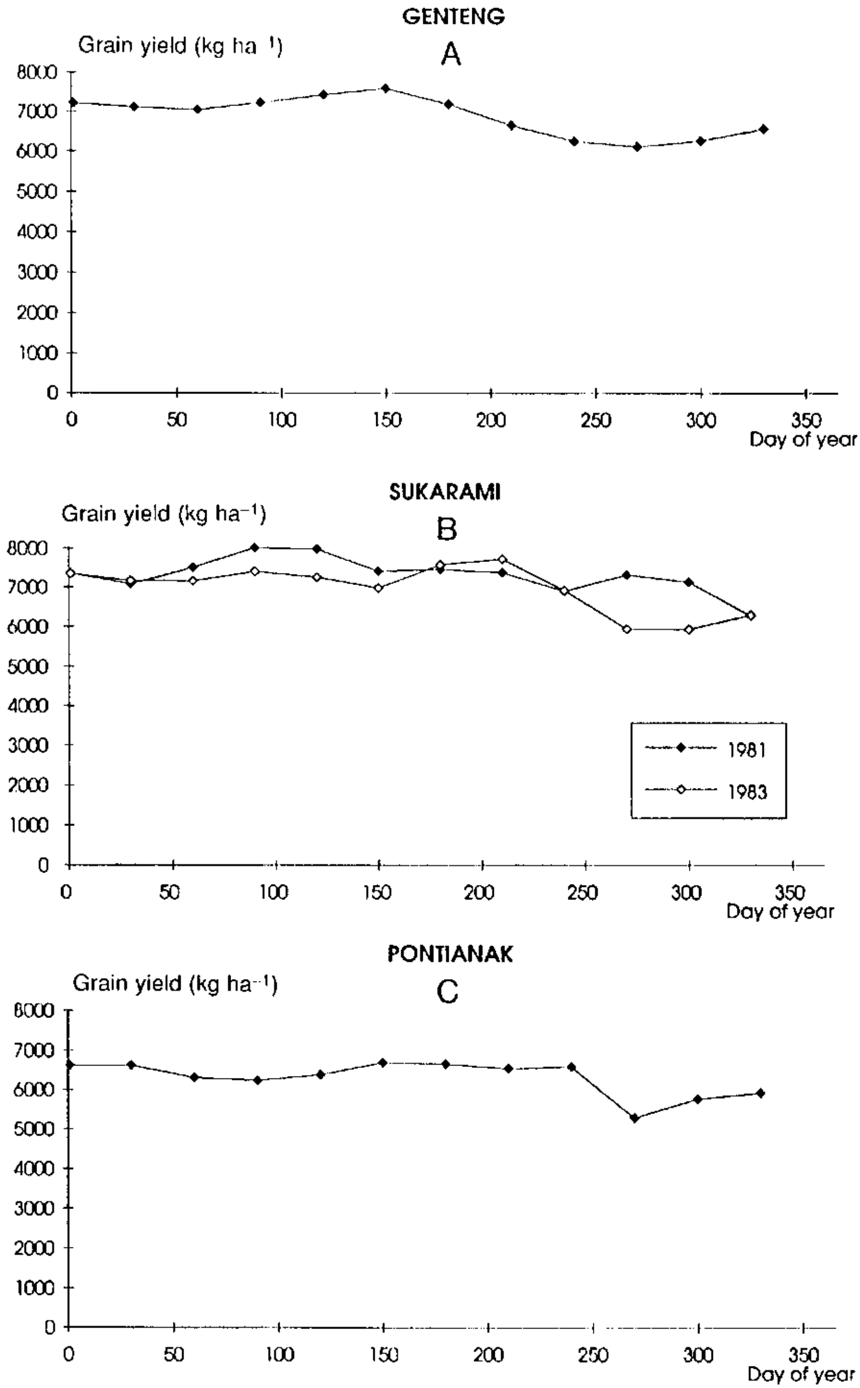
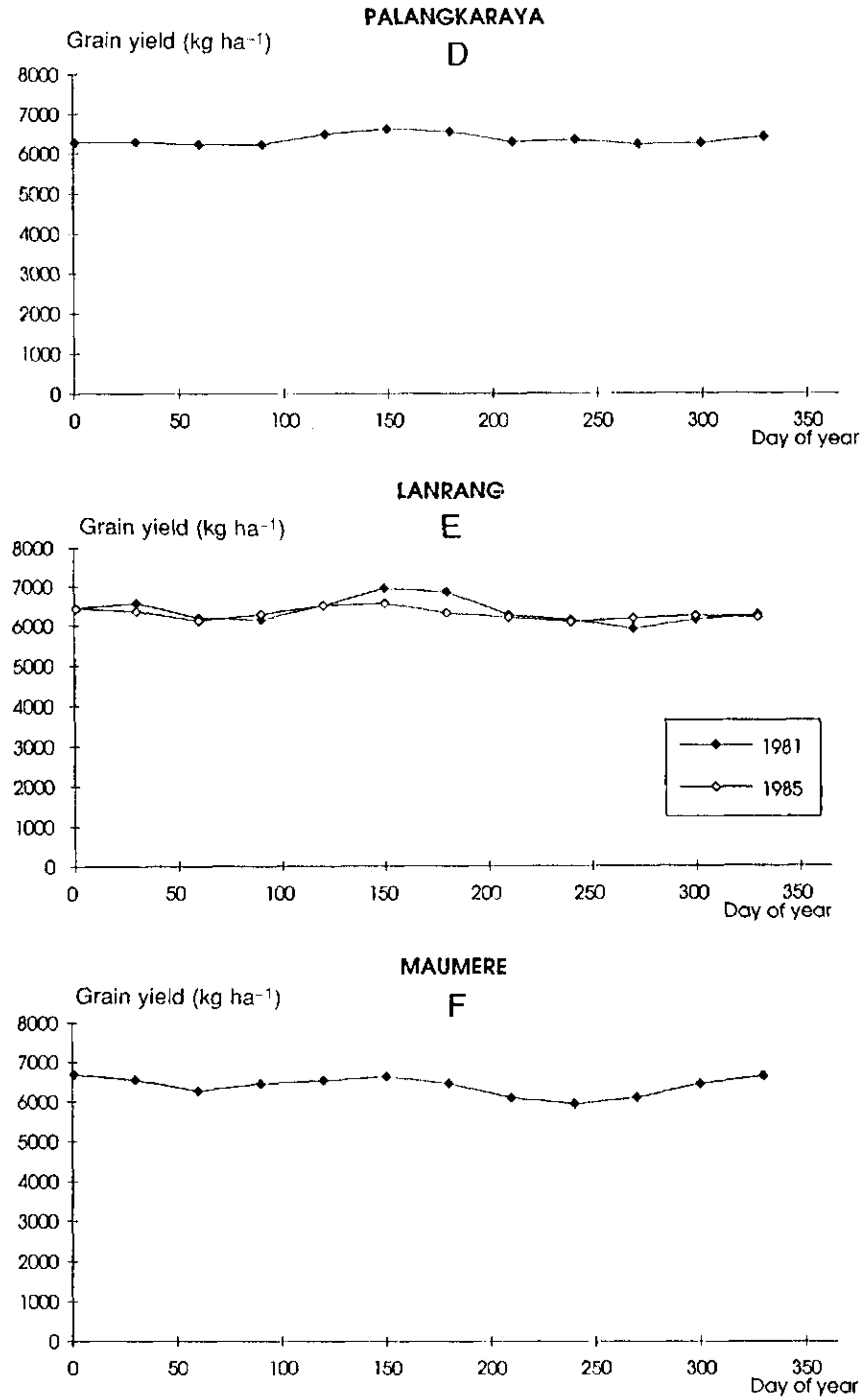


Figure 1. Potential rice yield as function of transplanting day in different agro-ecological sites in Indonesia. For Genteng, Pontianak, Palangkaraya and Maumere, the yields were simulated using average weather data (10 - 19 years). For Lanrang, yields were simulated for 1981 and 1985, for Sukarami, yields were simulated for 1981 and 1983.



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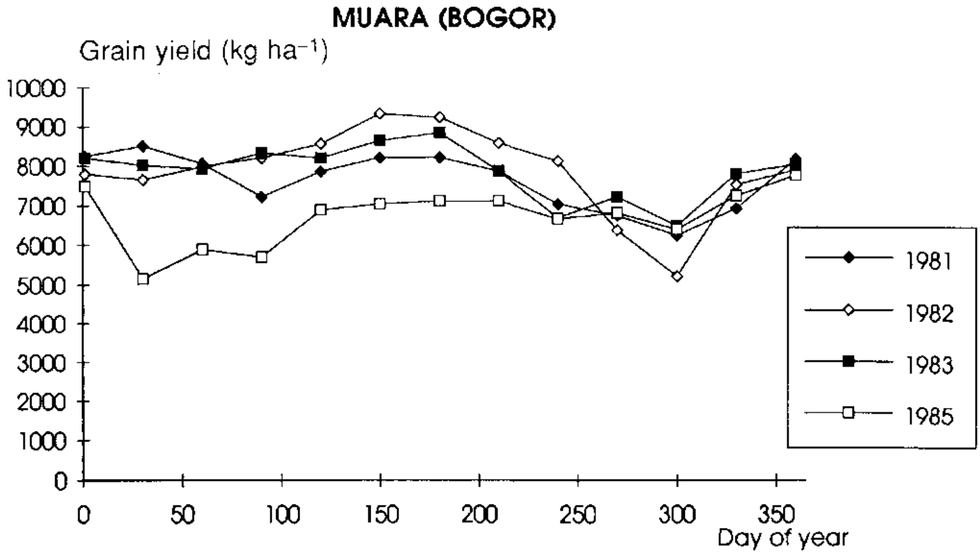

Figure 2. Simulated rice yield potential (kg ha^{-1}) at Muara/Bogor at different transplanting dates and in different years.

150) and the end of June (day 180) resulted in the highest average yield, the uncertainty (risk) was also very high. In contrast, transplanting between the end of December and the first of January resulted in a yield that was on the average lower than that of the May - June transplanting, but relatively stable from year to year. In practice, farmers usually transplant rice between late October (day 300) and the beginning of January (day 1) at the beginning of the rainy season, which is in accordance with the 'best' planting time predicted using the simulation work (most stable yields). However, for the second season (dry season), the farmers mostly transplant rice between early March and early April which results in unstable rice yields from year to year.

Comparing the highest (9333 kg ha^{-1}) and the lowest (5207 kg ha^{-1}) yield potential in 1982, and comparing the yields obtained under the four fictive climatic scenarios (Table 3), the following conclusions were drawn:

- The high yield potential with transplanting in end of May 1982 (day 150) is due to the 'best' solar radiation;
- The low yield with transplanting in late October (day 300) is due to the 'worst' solar radiation;
- The radiation during grain filling, namely 36 days before harvesting critically determined the rice yield potential.

Yield gap analysis

Actual rice yields between 1987 and 1990 of the seven locations varied greatly (Table 4). The highest actual yields are reached in Bogor and Genteng, both at Java. Farmers in Java

Table 3. Simulated potential rice yield in 1982 at Muara (Bogor), with two transplanting dates (day 150 and 300) under actual weather conditions and under four fictive 'climatic scenarios'. The four fictive scenarios are explained in the section Material and methods.

Transplanting date (day of year)	Temperature Maximum (°C)	Minimum (°C)	Radiation $MJ\ m^{-2}\ d^{-1}$	Yield potential $kg\ ha^{-1}$
150 (late May)	TMAX1	TMIN1	RAD1	9333
300 (late Oct)	TMAX2	TMIN2	RAD2	5207
Scenarios				
1: day 150	TMAX2	TMIN1	RAD1	10134
2: day 150	TMAX1	TMIN2	RAD1	9055
3: day 150	TMAX1	TMIN1	RAD2	5242
4: day 300	TMAX2	TMIN2	RAD2, RAD1*	8732

* the last 36 days is RAD1

Table 4. Actual and simulated rice grain yield at several locations (at District/Kabupaten level) in Indonesia.

Location	Yield ($kg\ ha^{-1}$) Actual	Simulated
Bogor, West Java	4717 - 4889	5575 - 9055
Genteng, East Java	4195 - 5749	6133 - 7418
Sukarami, West Sumatra	3820 - 5121	5939 - 8010
Pontianak, West Kalimantan	2163 - 2857	5280 - 6685
Palangkaraya, Central Kalimantan	1919 - 2576	6217 - 6601
Lanrang, South Sulawesi	3041 - 3243	5903 - 6944
Maumere, East Nusa Tenggara	2262 - 3412	5946 - 6659

generally have more and better technologies and facilities such as irrigation systems, soil cultivation, seed quality, fertilizers (mainly urea) and pesticides, and also better soil fertility compared to the sites in the outer islands.

The low actual yields of rice in the Kalimantan sites (Pontianak and Palangkaraya) are mostly due to the low soil quality, such as low pH, low nutrient content (mainly P and N) and high iron and aluminum content, and to poor soil management. The low actual yields of rice in Lanrang (south Sulawesi) and Maumere (east Nusa Tenggara) are due to water stress that occurs frequently during rice growth. Therefore, the gaps between the potential (simulated) and actual yields in the sites of the outer islands of Java are wide. Further study to eliminate the yield limiting factors efficiently is required.

In the Sukarami site (west Sumatra), the actual yield was almost similar to that of the sites on Java. Although the soil is not as fertile as in Java, the farm management by the farmers is as good as in Java.

The study of simulated rice yield potential within the year suggests a change in actual transplanting dates for several sites such as Genteng, Pontianak and Sukarami. Farmers mostly transplant rice in the period of October, November and December (rainy season) when the simulated yield potentials were relatively low. However, changing the date of transplanting is practically difficult because of irrigation water limitation, and social and economic constraints.

Conclusions

Simulation models can be used to analyse yield-limiting factors of rice, to perform risk analysis and yield-gap analysis. Further study to analyse and to solve the cause of yield gaps (potential versus actual) in specific agro-ecological environments with technical, economic and sociologic approaches are needed.

Agro-ecology, simulation and systems analysis approaches need to be adopted in Indonesia to support the effort of sustaining rice self sufficiency and food security. More agro-ecological sites that represent crop production centres are required to be involved in this kind of study.

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Crop simulation models as an analytical tool for delineation of production zones

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Abstract

The need for a simple, reliable and inexpensive method of extrapolating cropping systems technologies has long been recognized. One approach could be through the use of crop simulation models to estimate productivities of cropping systems technologies and, by integration with Geographic Information Systems (GIS) to define its production zones. This approach was illustrated for a case study in Isabela province in the Philippines. The user-friendly interactive model POLYCROP, that estimates crop yield of a sequence of crops grown in one year was extended with a Nitrogen model. This modified POLYCROP model was evaluated using data from on-farm trials conducted throughout the country. The Root Mean Square Error ('relative RMSE') and the *t*-test of the regression line of the predicted yield against the 1:1 line were used as validation criteria. For application of the model in Isabela province, model input on soil, land use and rainfall were available in a GIS. For a given set of technology, yields were predicted with the model POLYCROP and categorized into different yield ranges. Areas falling into the same yield range were grouped in production zones.

Introduction

In the past years, several on-farm verification trials have been conducted in different regions of the Philippines which seek to verify whether a newly developed technology is better than that of the current farmer's practice. If the new technology is found to be better, then it is considered to be recommended for dissemination in that particular area where the trial was conducted. Considering that the test sites cover only a relatively small area, it is essential to identify other areas in which similar results are expected in order to expand the scope of coverage. A procedure commonly used is the multilocation testing, wherein verified technologies are tested on a number of farms in 'suspected' similar production zones. However, this process is expensive and requires relatively long periods of testing. The potential of crop simulation models as a simple, reliable, fast and inexpensive method of extrapolating recommended technologies should be explored (Garrity et al., 1988). Hopefully, crop simulation models could be good instruments in the determination of the boundaries where the new technology could be disseminated for farmers' use.

This paper focuses on the strategy of using crop simulation models complemented with geographic databases as a simple analytical tool in determining the production zones of a particular technology. Production zone is defined here as a geographical area with a particular yield range obtained using a specific recommended technology (comparable to 'recommendation' domain). In the following sections, our experience of defining production zones in the Philippines will be discussed.

Description of methodology and results

The procedure developed to use crop growth simulation models in defining production zones consists of three steps: 1) development of crop simulation models that require easily available data and that have good potential to predict yield over a wide range of environmental conditions, 2) evaluation of the model's predictive ability, and 3) application of the model to calculate crop yields and to identify the production zones. A flow diagram of the procedure is given in Figure 1.

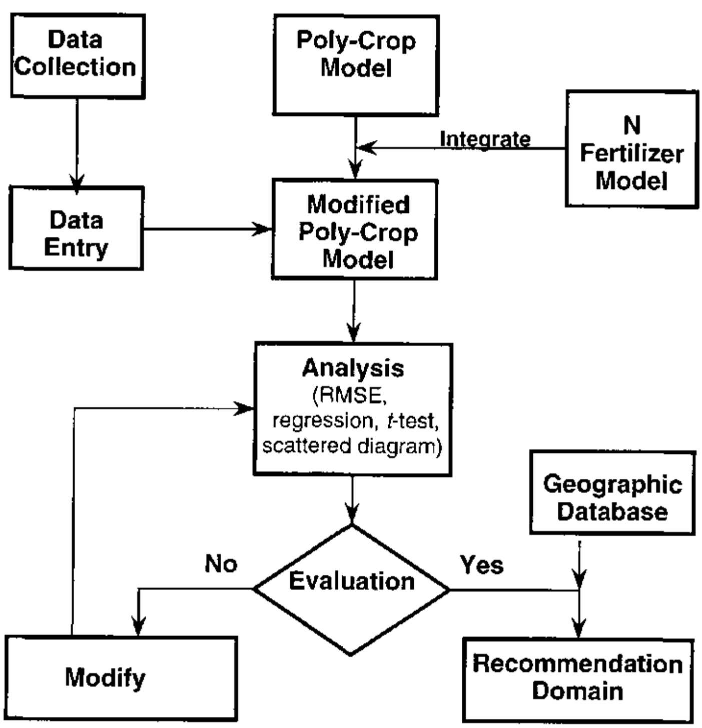

Figure 1. Flow diagram of the procedure of using crop simulation modelling and Geographic Information Systems (GIS) in identifying and delineating production zones.

Step 1: the simulation model POLYCROP

A model with a good potential to predict crop yields over a wide range of environments was selected based on the following criteria:

- Simplicity and ease of running, i.e. required input data should be easily available, and the model should be user's friendly, and
- Flexibility in incorporating additional features in the model.

From the many models that satisfy these criteria, we have (initially) selected the model POLYCROP (Angus et al., 1987; Garcia, 1987a, b; Angus & Garcia, 1988) to demonstrate our procedure. Later, the model POLYCROP was modified by integrating the Nitrogen subroutine of the model CORN (Garcia, 1979).

POLYCROP is an interactive water balance - crop yield model that provides estimates of productivity of crops that are grown in sequence in relation to weather and soil type. Thus, long-term opportunities for sequential cropping can be evaluated by using this model. The original model was adapted to enable researchers and production technicians to test the productivity of rice-based cropping systems in relation to changes in the number and types of crops, and in relation to changes in management factors, e.g. turn-around time, crop variety (especially growth duration).

The model is applicable for both upland and lowland rainfed environments. It requires the following input data: daily rainfall, weekly potential evapotranspiration, soil characteristics, cropping sequence, and crop characteristics. Soil input data are infiltration rate and the soil water content at saturation, at field capacity and at wilting point. Input parameters for cropping sequence and crop characteristics are: the number and type of crops to be planted within a year, crop development characteristics (days to anthesis and maturity), maximum rooting depth, maximum percentage foliage cover and crop water use efficiency.

Data files containing daily rainfall for 104 stations in the Philippines were used in the model. Evaporation data were obtained for 29 locations from estimates by Tamism (1977) based on the Penman equation. Since measured evaporation data are not widely available, the method of Wahba (1979), as applied by Hutchinson et al. (1984) was used for the remaining 75 rainfall locations. Weekly mean rates were calculated from the mean monthly rates using the method of cubic Bessel interpolation as described by Boor (1978).

The model output consists of crop yields, estimated total transpiration, sowing date and harvest date.

The major limitations of the model are:

- The model is only applicable for sequential cropping and not for intercropping or mixed cropping.
- Estimated yields are most accurate for crops whose yields are harvested after flowering. For example, yields of leafy vegetables and of sugarcane are not well estimated.
- Rainfall is considered as the sole source of water; irrigation is not taken into account.
- Since POLYCROP is just a simple water balance model, it does not take into account other factors such as soil fertility and pest and disease occurrence.

The Nitrogen fertilizer model was extracted from the model CORN (developed by Garcia, 1979), which predicts yield using the equation:

$$PY = MAX \times (1 - YR_N) \qquad (1)$$

where

PY is the predicted yield,
MAX the simulated yield using POLYCROP, and
YR_N the yield reduction due to the factor Nitrogen.
The inputs for the N fertilizer model are soil organic matter and N fertilizer.

Step 2: evaluation of the modified model POLYCROP

First, data were selected for the validation of the modified model POLYCROP. Since 1983, the Provincial Technology Verification Trials (PTVT), conducted by the Department of Agriculture in different regions of the country, have accumulated a mass of data from on-farm trials. The data include weather data (rainfall, solar radiation, temperature, relative humidity) if available near the experimental site, soil data, crops planted, input used (fertilizer, chemicals, etc.), crop yields and cost of inputs for economic analysis. Furthermore, data from the National Cooperative Tests (NCT) conducted all over the country were obtained .

Although a lot of data were collected, only a few data were actually used for model validation and evaluation. A number of experimental trials did not have data needed by the model (namely rainfall). Table 1 shows the number of experiments and source of the data for the different crops used in the validation.

Initially, several statistical procedures and measures were used to test the validity of the modified model POLYCROP, namely: correlation coefficient, regression, *t*-test and root mean square error (relative RMSE). Graphical analysis by plotting the predicted yields and the actual yields in a scatter diagram was also used. Later, we used only two criteria to determine whether the model is acceptable or not:

1 The relative RMSE should be lower than 0.25, and
2 The *t*-test of β between the 1:1 line and the regression line between predicted and actual yields should not be significant.

The test procedure should not be complex so that individual judgment will also remain an important factor contributing to the final evaluation of the model.

To determine the degree of deviation of the predicted yield from the actual yield, error analysis was done for paired comparisons of these values. The relative RMSE was computed by the equation (Pindyck & Rubinfeld, 1981):

$$RMSE = [((Y_a - Y_p) / Y_a)^2] / N \qquad (2)$$

where

Y_a is the actual yield,

Y_p the predicted yield, and

N the number of paired comparisons.

The hypothesis tested for the t-test was:

$$H_0: \beta = 1$$

where

β is the slope of the linear regression line between predicted and actual yield.

Although the model takes cropping patterns into account, validation was done for single crops only. The model's performance was evaluated for rainfed lowland rice, corn and mungbean. Figure 2 shows the relationship between predicted yield and actual yield of

Table 1. Experimental data used in the validation of the modified model POLYCROP. (National Cooperative Test (NCT); Provincial Technology Verification Trial (PTVT)).

Crop	Source	Location	No. of trials
Rice	NCT	Laguna	1
	Ilagan		2
	Camarines Sur		3
	PTVT	Mindoro Occ.	10
	Lanao del Norte		2
	Palawan		3
	Southern Leyte		3
Corn	NCT	Isabela	4
	Negros Occ.		4
	Palawan		1
	Cebu		1
	Laguna		1
	Bohol		2
	Bukidnon		4
	Camarines Sur		3
	PTVT	Albay	4
	Batangas		4
Mungbean	PTVT	Romblon	6
	Palawan		3
	Rizal		2
	Pangasinan		4

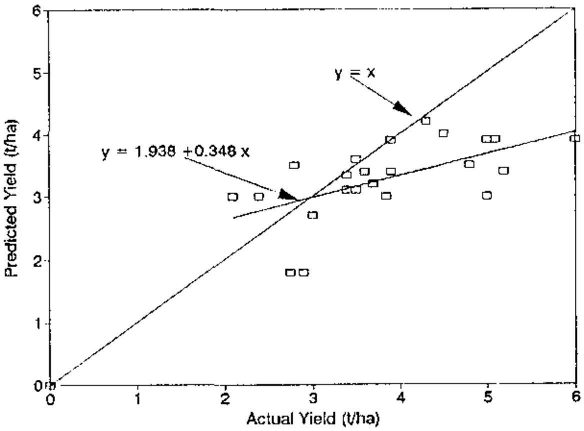

Figure 2. Predicted versus observed yield of rainfed lowland rice using the modified model POLYCROP. The drawn lines are the linear regressions. (t=0.76, RMSE=0.24, N=24)

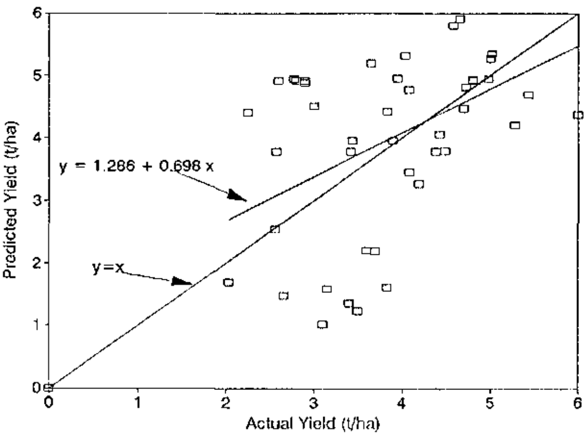

Figure 3. Predicted versus observed yield of corn using the modified model POLYCROP. The drawn lines are the linear regressions.
(RMSE=0.40, N=48)

rainfed lowland rice. The relative RMSE is only 0.24 which satisfies the first criteria (see above). However, the *t*-test was significant, which means that the second criteria was not met. Figure 3 shows the scatter diagram for corn with 48 data pairs. The relative RMSE was 0.40 and the *t*-test was significant, meaning that the two criteria for validation were not met. However, when we separated the data for model validation into a group where the experimental sites were within 5 km distance of the rainfall recording site, and a group where the sites were more than 5 km away, different results were obtained. Figure 4 shows that the relative RMSE was 0.23 and the *t*-test was not significant when the rainfall data were collected within 5 km from the experimental sites, indicating that the model validation criteria were satisfied. On the other hand, when the experimental sites were more than 5 km away from the rainfall recording site, the relative RMSE was high (0.55) and the *t*-test was significant. This result indicates the importance of using rainfall data collected near the experimental site.

The validation results for mungbean are shown in Figure 5. The relative RMSE was within acceptable level (0.13), but the *t*-test was significant.

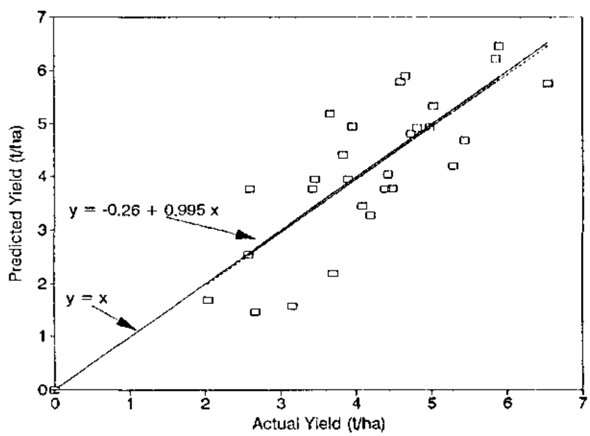

Figure 4. Predicted versus observed yield of corn using the modified model POLYCROP with rainfall data recorded within 5 km distance from the experimental site. The drawn lines are the linear regressions. (t=0.32, RMSE=0.23, N=28)

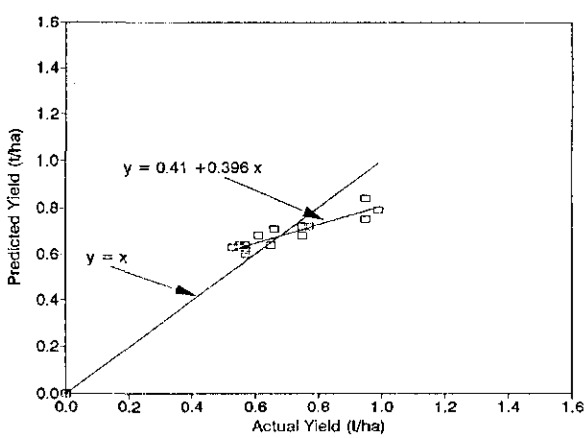

Figure 5. Predicted versus observed yield of mungbean using the modified model POLYCROP. The drawn lines are the linear regressions. (t=12.9, RMSE=0.13, N=15)

Step 3: identification of production zones

The model predicted yields by inputting the required parameters, but it was not capable to geographically delineate zones of comparable production, i.e. the production zones. For the production zones to be delineated, there is a need to identify the boundaries between input parameter values on maps. Mapping the parameters required by the model can be done manually but the process becomes complicated when analysis, upgrading and integration of data sets is needed. The process could be substantially improved by using a Geographic Information System (GIS) as a data storage, manipulation and mapping tool. In a GIS, parameters such as land use, soil properties and climate can easily be re-grouped and delineated as new mapping units. Using Isabela province in the Philippines as case study, we will illustrate our methodology by using the modified model POLYCROP combined with a GIS in identifying and delineating production zones. Maps of soil type, existing land use and rainfall were generated as follows:

Soil map The soil map was based on the Soil Survey of Isabela province by the Bureau of Soils (1969) (Figure 6). The soil units were delineated based on soil series, soil type and organic matter content. Except for the organic matter content which was taken from the Soil Survey Report, the information needed as model input (namely infiltration rate, water contents at various pressure heads) was derived from the soil survey map.

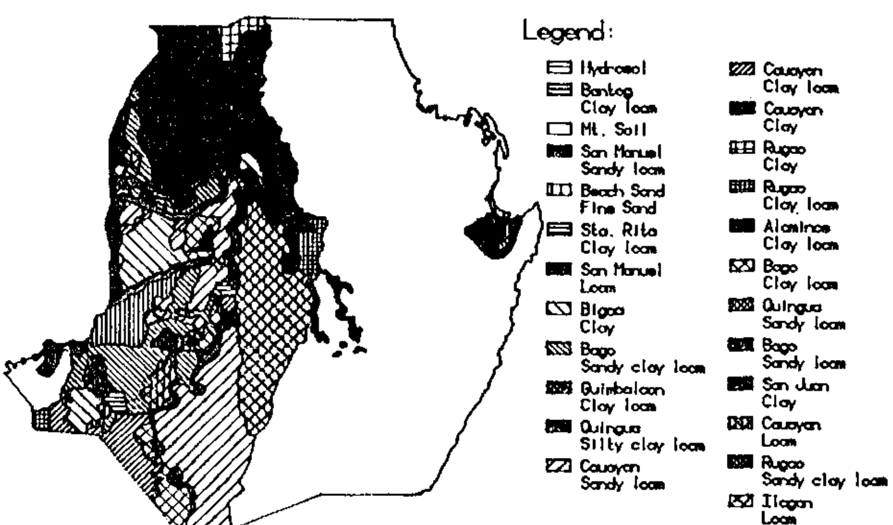

Figure 6. GIS-based soil map of Isabela province in the Philippines.

Land use map The land use map was generated from information from the Bureau of Soils (1966). Since we used rainfed lowland rice, corn and mungbean in the modified model POLYCROP, areas suitable for these crops were mapped.

Rainfall map The rainfall map was generated using the Thiessen method. This interpolation method 'assigns' geographical areas to point observations such as made by meteorological stations. Although Isabela province is a mountainous area, which makes spatial interpolation of rainfall data using the Thiessen method not very reliable, this method was still used because no better alternatives were available. Four rainfall stations were used to delineate rainfall areas (Figure 7).

The soil map, the land use map and the rainfall map were integrated and the parameters of every resulting mapping unit were used as input in the modified model POLYCROP. This spatial information was coupled with other data required by the model in order to simulate crop yield and to delineate production zones. An illustration of the production zones of lowland rice is given in Figure 8. The rice variety used had 90 days growth duration, and was planted on May 1 and July 1 (Figures 8A and B, respectively).

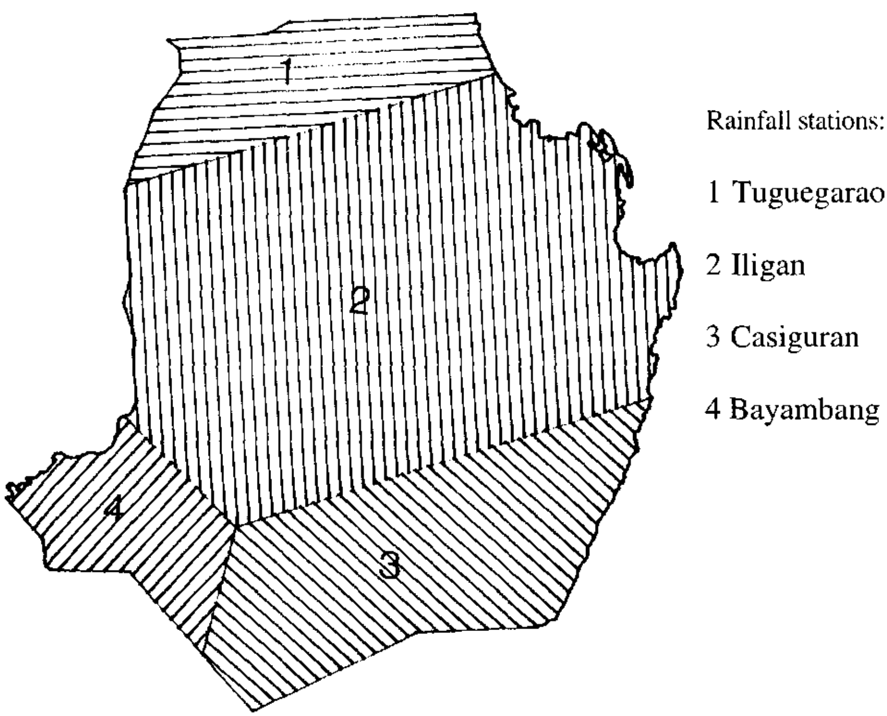

Figure 7. GIS-based rainfall map showing the areas allocated to the four rainfall recording stations in Isabela province.

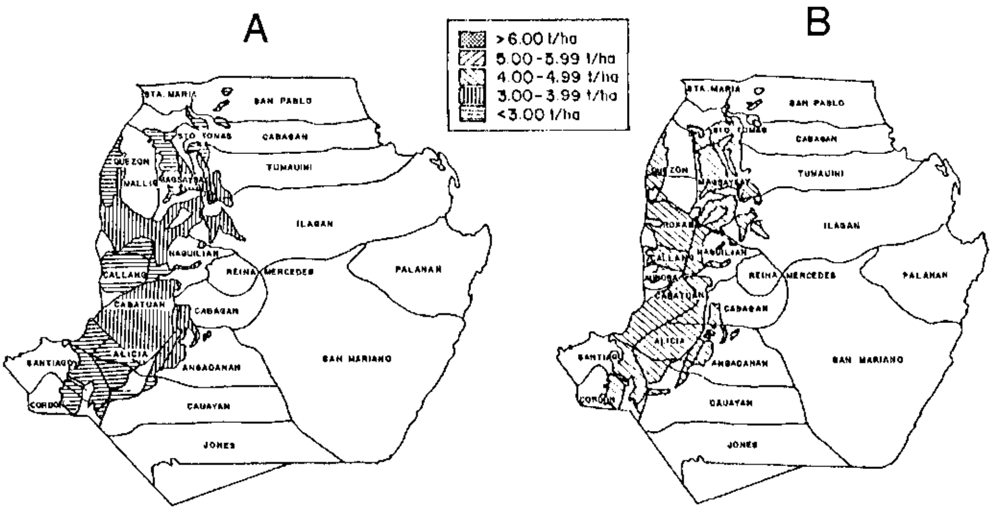

Figure 8. Predicted yield of rainfed lowland rice in Isabela province, using the modified model POLYCROP with transplanting dates May 1 (A) and July 1 (B).

Conclusions and discussion

The methodology described in this paper illustrates the potential of crop simulation models as a tool and guide for researchers, policy makers and extension workers in decision-making and planning. Some applications are:

- Target production areas can easily be identified for a given set of technologies. Areas with high yield potential may be selected for production programs.
- Suitable varieties (namely with respect to growth duration) and the cut-off dates for planting can be determined.
- In areas with low yield potential, researchers can examine possible technologies that may improve productivity. Such technologies could then be input in the simulation model to determine which ones would give the best results.

Based on our experience in the Philippines, some comments can be made with regard to model development and model validation:

Model development Models are usually developed with only a few factors being considered that greatly influence crop growth. A model that has an intention of being used for extrapolation of production zones should be flexible in terms of allowing incorporation of other factors which are deemed important in a given location. For example, phosphorus may not be an important factor in an environment where the amount of phosphorus in the soil is relatively high. However, under strongly acidic soil conditions, the availability of phosphorus is very important.

Model validation To have a more reliable model validation, more data sets are needed. In our study, some data needed for model validation were not always available from the PTVT trials. For example, rainfall data were not always recorded at the experimental site. In such cases, rainfall data were collected from the nearest rainfall station which was often several kilometres away from the experimental site. As has been shown, rainfall data collected more than 5 km away from the experimental site were not suitable for model validation. Furthermore, very few reports on unsuccessful trials were available. This kind of information/data is equally important in model validation because it could test whether the model will also indicate crop failure.

Although no definite set of criteria is recommended for validation, the combination of relative RMSE, *t*-test and scatter diagram seems to be a good yardstick.

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Simulation analysis of risk and uncertainty in crop yield due to climatic variations and change

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Abstract

Crop growth simulation modelling was used to assess the risk and uncertainty in rainfed upland rice production associated with climatic variations and change at Los Baños and Davao in the Philippines. The mean and quartile values, and exceedance probabilities of simulated rice yields for each month of transplanting throughout the year were calculated. The results show that expected yields for a rice crop grown under rainfed (upland) condition are high during the wet season, and low during the dry season in areas where the prevailing climate is characterized by pronounced wet and dry seasons. The low risk periods coincide with the wet periods. Simulation results for the anticipated future climatic conditions indicate increased crop yields, higher yield exceedance probabilities, particularly for lower yield levels, and longer optimal crop growing periods.

Introduction

Evaluation of risk and uncertainty due to the vagaries of weather is of considerable importance in crop management. Weather variations as well as the anticipated changes in climatic variables (e.g. carbon dioxide concentration, temperature) can affect plant growth, crop production and eventually worldwide trade of staple foods (Geng & Cady, 1991). There are two basic methods in evaluating relationships between weather and crop performance. In the first method, the *statistical or correlation method*, empirical relations are determined between yield and one or more weather variables. The relationships may vary in the number and type of weather variables, and may apply for specific locations or regions only. Although statistical models can provide reasonable quantification of weather effects, they require a large data set on crop yield and weather variables.

The second approach is by using *crop growth simulation models*. A crop growth model is a simplified representation of crop growth based on an understanding of the physiological processes involved. Such models can be used to determine crop behaviour under specific environmental conditions, such as weather. Several crop simulation models have already been developed and documented (e.g. Penning de Vries et al., 1989; McMennamy & O'Toole, 1983), and have been demonstrated to give satisfactory results. Figure 1 shows a relational diagram of a model for crop growth under optimal conditions, i.e. optimum supply of water and nutrients, and no pest and disease problems. The relations among key crop growth processes such as photosynthesis, maintenance respiration, and assimilated partitioning are indicated, as are the effects of weather variables as light and temperature. Since the model is process-based, other process components may be introduced without changing its basic form. For instance, a crop growing under limited water conditions may be modelled by incorporating a soil water balance component into the basic crop model (Figure 2). Likewise, the effects of pests and diseases on crop growth can be introduced.

Since crop growth models consider key ecophysiological processes affecting crop growth and development, many input data are required for simulation. Aside from crop data and weather data, the model may require soil data (e.g. soil depth, number of soil layers, hydraulic characteristics, etc.).

In this paper, an assessment of risk and uncertainty in rainfed rice yield due to present climatic variations and future (anticipated) climatic change is made via crop growth simulation for two locations in the Philippines. Risk and uncertainty are quantified in terms of variation in simulated rice yields.

Material and methods

Climate in the Philippines

The Philippines has a tropical climate that is conducive to crop production throughout the year. The climate is generally characterized by four climatic types in terms of the relative duration and intensity of the wet and dry seasons. Climate type 1 climate has two pronounced seasons: a wet season from May to November and a dry season from December to April. Climate type 2 has no clear dry season, and maximum rainfall occurs between November and January. Climate type 3 has no pronounced wet and dry season, but is relatively dry from November to April. Climate type 4 has rainfall more or less evenly distributed throughout the year. Figure 3 shows the distribution of these four climate types in the Philippines.

The Philippines is visited by typhoons at an average of 20 typhoons yearly (Figure 1), mostly occurring on the eastern and northern sides of the archipelago. Typhoons occur usually from June to October and cause significant damage to agricultural crops during the wet season.

The crop growth simulation model

The crop growth model MACROS - module L1D (Penning de Vries et al., 1989; see also Figure 1 and the description above) coupled with the SAHEL water balance was used. The model simulates rainfed upland rice growth under optimum availability of nutrients and without pest or disease infestation. The soil type considered was a deep clayey soil (though under freely draining conditions and with a deep groundwater table). Crop data for the variety IR36 were taken from Penning de Vries et al. (1989) while soil data were obtained

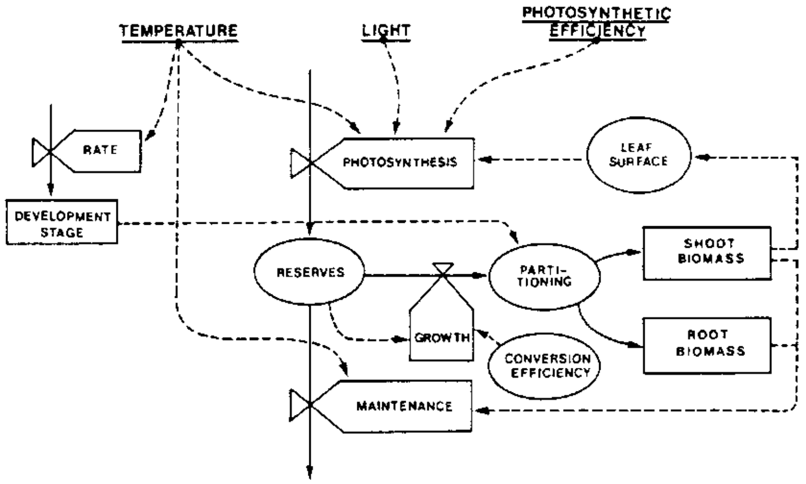

Figure 1. Relational diagram of a model of a crop growing under optimum growing conditions (only radiation and temperature affect growth and development). Source: Penning de Vries et al., 1989.

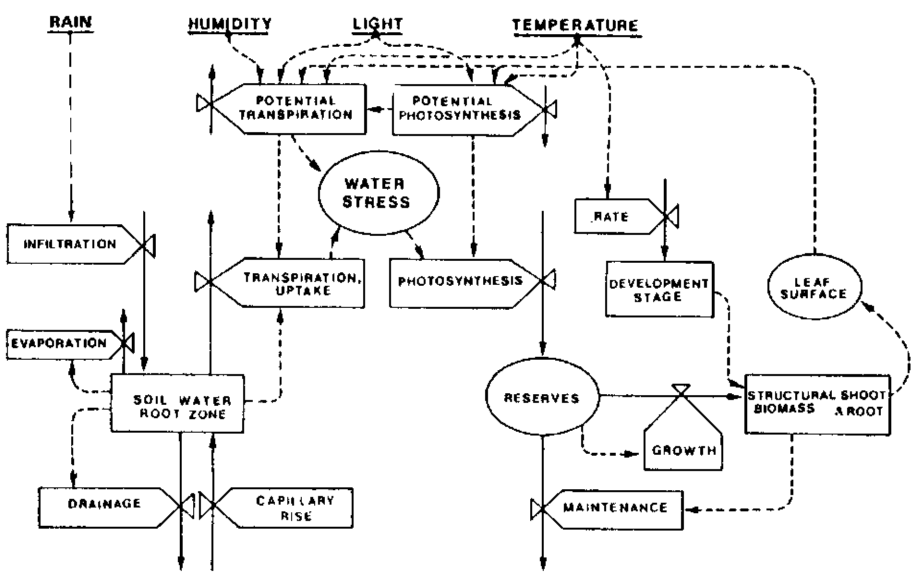

Figure 2. Relational diagram of a model of a crop growing under water-limited conditions. Source: Penning de Vries et al., 1989.

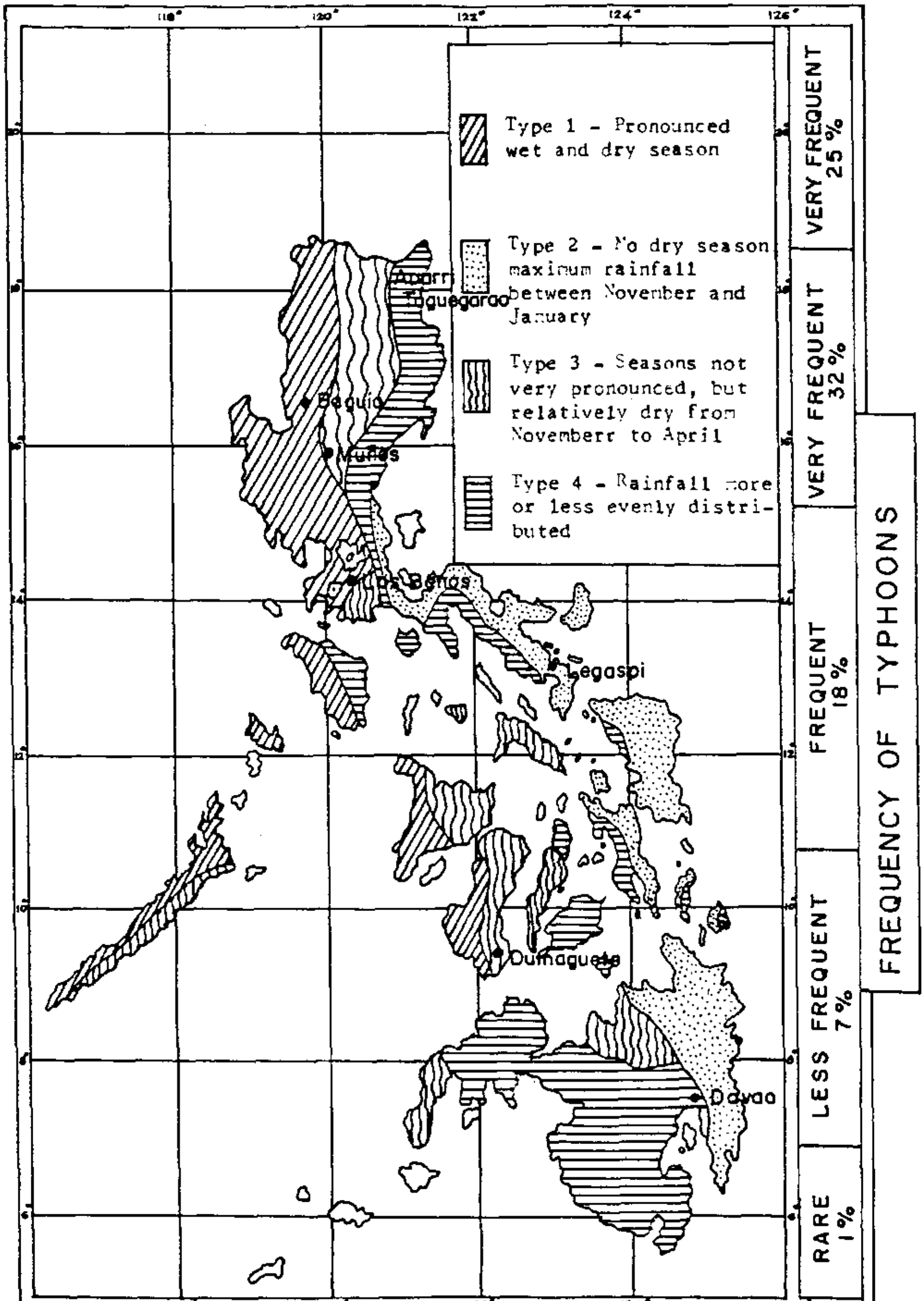

Figure 3. Climate map of the Philippines showing the location of Los Baños and Davao (used in this study). The relative frequency of occurrence of typhoons is also indicated. Source: Philippine Weather Bureau.

from a field study conducted in Los Baños (Legaspi et al., 1989). Crop growth was simulated for different transplanting dates using weather data from two locations, representing different climate types (see above): Los Baños for climate type 1, and Davao for climate type 4 (Figure 3). Historical daily weather data from 20 years were used as model input for Los Baños while a combination of five years of historical and 15 years of generated daily weather data were used for Davao. The generated weather data were computed using the SIMMETEO package (Geng et al., 1988; Lansigan & Casumpang, 1993, this volume) which has been demonstrated to give statistically reliable results compared to historical records (Lansigan & Sanchez, 1991).

To quantify the effects of climatic change on rice yields, this study assumed an anticipated climatic scenario of elevated air temperature and carbon dioxide concentration consistent with predictions by most GCMs (Global Circulation Models, e.g. Jenne, 1989). In the 20 years of weather data for Los Baños and Davao, 1.5 °C was added to the daily temperatures and the CO_2 concentration was multiplied by 2. Possible change in rainfall was not considered in the study. Moreover, while typhoons cause damage to the crop, their effects are not considered because the current GCMs are unable to make reliable predictions of the frequency and intensity of typhoons in future climates.

Results

Rice yield under current climatic conditions

Median yields including the first and third quartile yields were calculated to indicate yield variability. The yield variability index was computed as the percentage difference between the first and third quartile yields relative to the median yields. Risk analysis likewise considers the probability of exceedance of specified yields.

Figures 4 and 5 show the simulated rainfed rice yields and corresponding yield variabilities for each month of transplanting for Los Baños and Davao. Rice yields were relatively high (at least 4 t ha^{-1}) and stable (a yield variability index less than 20%) during the wet season. The figures also indicate that the 'low-risk' or optimal cropping period in Los Baños, with pronounced wet and dry seasons, is shorter than in Davao where rainfall is evenly distributed throughout the year. Thus, rainfed rice may be grown in Davao almost anytime of the year.

Figure 6 shows the weather-related risk and uncertainty in rice production in terms of probability of exceedance of specified yields. The curves indicate higher reliability in achieving specified yield levels in the wet season than in the dry season. The figure also shows that while the median yields are almost the same for the two sites, the exceedance probabilities for low yields are higher in Davao than in Los Baños.

Rice yield under anticipated future climatic conditions

Figure 7 shows the exceedance probabilities of rice yield levels in the wet season at Los Baños and Davao under the current and anticipated future climatic conditions. The yield

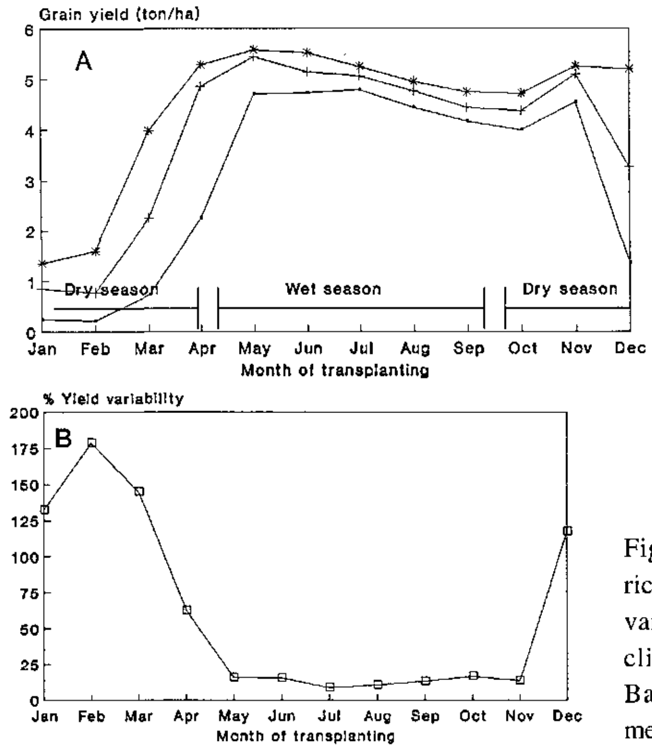

Figure 4. Simulated rainfed rice yield (A) and rice yield variability (B) under current climatic conditions at Los Baños. (25% quartile (•); median (+); 75% quartile (*))

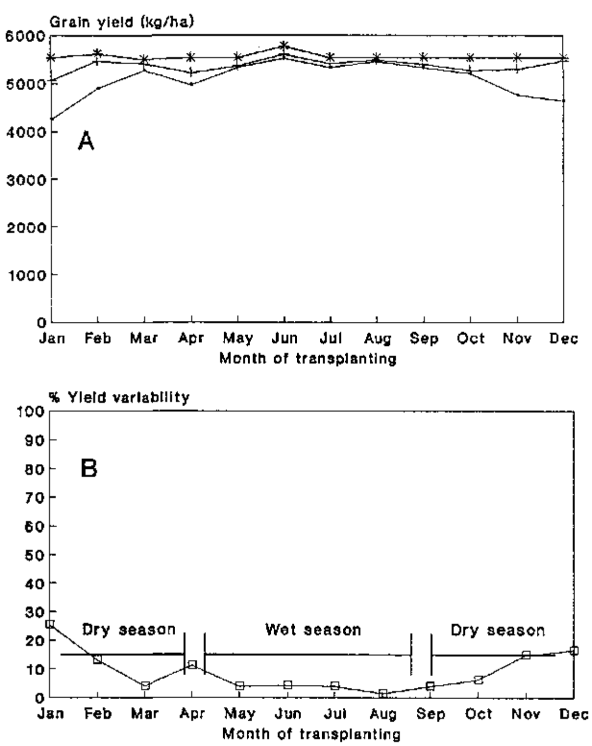

Figure 5. Simulated rainfed rice yield (A) and rice yield variability (B) under current climatic conditions at Davao. (25% quartile (•); median (+); 75% quartile (*))

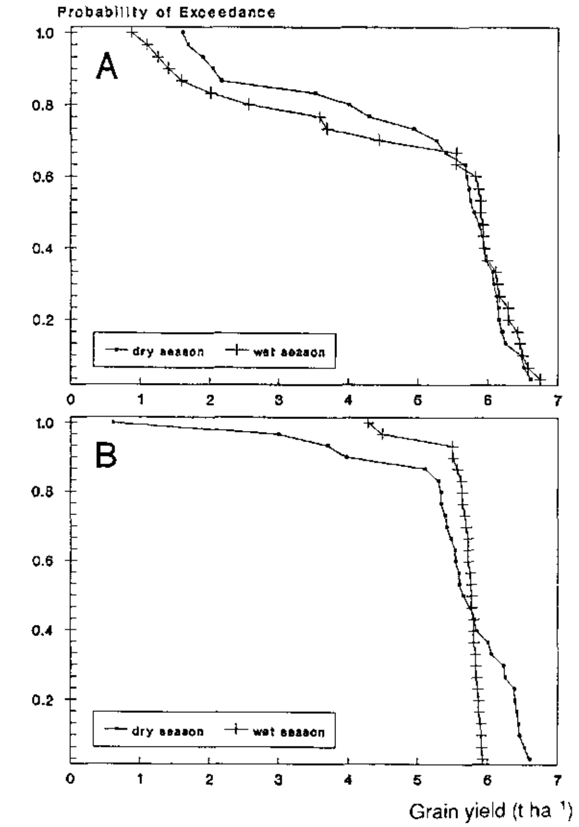

Figure 6. Exceedance probability curves under current climatic conditions for rainfed rice yield in the dry and wet season at (A) Los Baños and (B) Davao.

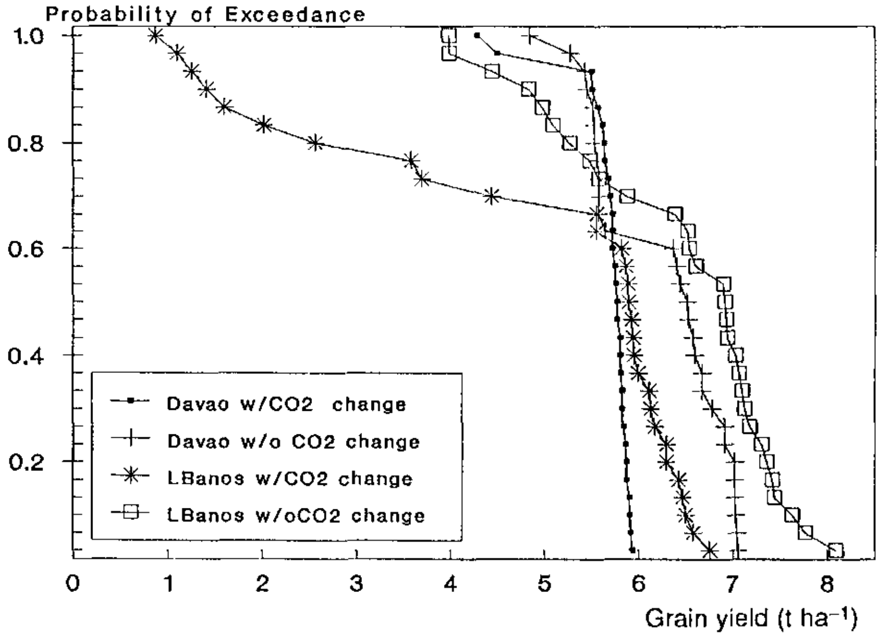

Figure 7. Exceedance probability curves of wet-season rice yield at Los Baños and Davao under current and anticipated future climatic conditions.

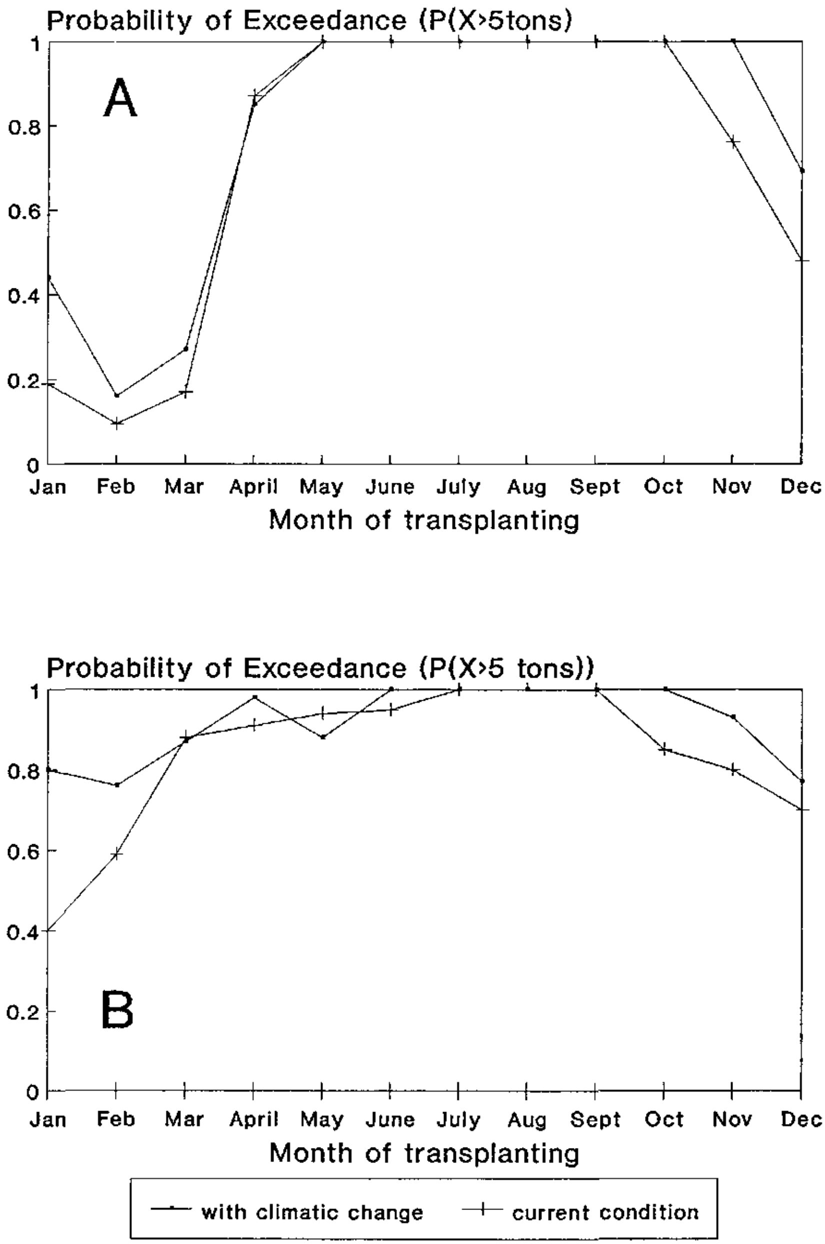

Figure 8. Monthly probabilities of exceeding 5 t ha^{-1} rice yield under current and anticipated future climatic conditions at (A) Los Baños and (B) Davao.

exceedance probability curves are different for the current and the future climatic conditions, particularly for the lower yield levels.

Figure 8 shows the monthly exceedance probability curves for rice yields of 5 t ha^{-1} in Los Baños and Davao, under the current and the anticipated future climatic conditions. The probability of exceeding 5 t ha^{-1} is higher under the anticipated future climatic conditions than in the current climatic conditions. During the November - March transplanting at Los Baños, the growing period is expected to be prolonged by one month under future climatic conditions. At Davao, the optimal cropping period is expected to be prolonged by at least two months.

Conclusions

Risk analysis of crop yields due to climatic fluctuations and with expected climatic change may be evaluated in terms of variability of simulated yield. Two useful measures of assessing crop yield variability are the yield variability index and the yield exceedance probability curve. These measures may be simulated by a process-based crop simulation model with observed or generated weather data as model input. Such a model can also be used to evaluate the probable effects of anticipated changes in climatic variables e.g. increases in temperature, and CO_2 levels.

Analysis of simulated yields and yield variabilities at Los Baños and Davao, the Philippines, indicates that crop yields will increase on the average by about 15% and 8% respectively, under anticipated climate change condition. Moreover, the optimal growing period will be prolonged by 1 month in Los Baños and by 2 - 3 months in Davao. The probability of exceeding specified yield levels, particularly low yield levels, is higher under the anticipated future climate than under the current climate. The results also suggest that the possibilities for rainfed upland rice cropping in Los Baños and Davao improve with the anticipated climate change.

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IMSP: Interactive Meteorological data Simulation Program

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IMSP, or Interactive Meteorological data Simulation Program is a user-friendly and enhanced version of the weather data generation software SIMMETEO (Simulation of Meteorological Variables by Geng et al., 1988). It is a direct translation of SIMMETEO, written in Fortran 77, to Turbo Pascal 5.5, with some added features: an interactive menu system, data management capability, and graphics facility, thus providing an interactive user's interface to the system. IMSP requires an IBM PC/AT or XT microcomputer (or compatible) with at least 512 KB of Random Access Memory (RAM), CGA card and monitor, two floppy disk drives or a hard disk, and an MS-DOS version 3.0 (or higher). The system can be run on a microcomputer without a mathematical microprocessor because Turbo Pascal 5.5 can emulate a numeric coprocessor using its emulator library. A menu system was added to fully implement the interactive interface of the program. A full-screen data management system is also included to provide easier entry, editing, saving and retrieval of data. It uses the conventional ASCII as in- and output data format. The graphics facility enables graphical visualization and also comparison of the historical and generated sequences of weather variables. Copies of overlay plot of historical and generated data can be send to a printer.

IMSP requires at least two-year sequences of daily values of weather variables or monthly summaries of weather data: fraction of wet days (i.e. number of wet days/total number of days in a month); amount of rainfall (i.e. total volume of rainfall/number of wet days in a month); maximum and minimum temperature; solar radiation; humidity and wind speed. The weather data can be in any unit of measure since the system allows the user to change the unit of the input variables. If the units of the input and the output variables are different, the system automatically converts them into standard units used in the system. Input data can be created using the IMSP data management system or any text editor.

Statistical evaluation of the generated sequences of meteorological variables using IMSP showed reasonably good results. However, simulation of the occurrence of extreme events such as typhoons is not yet incorporated in the system.

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Simulation of the effects of sowing and transplanting date on the duration and potential yield of several crops and cropping systems in Danyang County, Jiangsu Province

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Abstract

A crop growth simulation model (module L1D from the model MACROS) was used to analyse the effects of sowing and transplanting date on the duration and potential yield of several grain crops and three cropping systems in Danyang County in Jiangsu Province, China. The simulated potential yield of barley-early rice-late rice cropping averaged 21600 kg ha^{-1}, that of wheat/interplanted corn-late rice cropping about 20300 kg ha^{-1}, and that of wheat-single rice cropping about 15800 kg ha^{-1} between 1986 - 1990. The barley-early rice-late rice system, however, had a high 'climatic risk', very short periods between harvest and transplanting of consecutive crops, and very low net profits. The introduction of corn into the local cropping pattern by the wheat/intercropping corn-late rice system fully utilizes local climatic resources, and increases annual yield and economic return above the current wheat-single rice double cropping pattern. In Danyang County, there is a large yield gap between actual and simulated potential yields of wheat, barley and corn, which is mainly caused by inadequate drainage conditions. The highest actual (single) rice yields reach simulated potential values.

Introduction

Cropping intensities in southern Jiangsu Province, China, are high because of limited farmland and a large population pressure. Farmers generally grow two or three crops annually to meet consumer's needs. Danyang County, located on the southern low reach of the Yangtsi River Valley, has a subtropical monsoon climate, with annual average temperature and rainfall, and total annual daily light hours of 14.9 °C, 1052 mm and 2090 h respectively (28 year recording). The traditional cropping systems are wheat-single rice and rape-single rice double cropping (Figure 1A), and barley-early rice-late rice triple cropping (Figure 1B). Double rice cropping systems were adopted in large areas in the 1970s, but declined in recent years because of high labour intensities, high costs and unstable yields. Today, new triple cropping systems with more favourable economic returns emerge, e.g. a wheat or barley winter crop, interplanted with corn or soybean in spring, and followed by

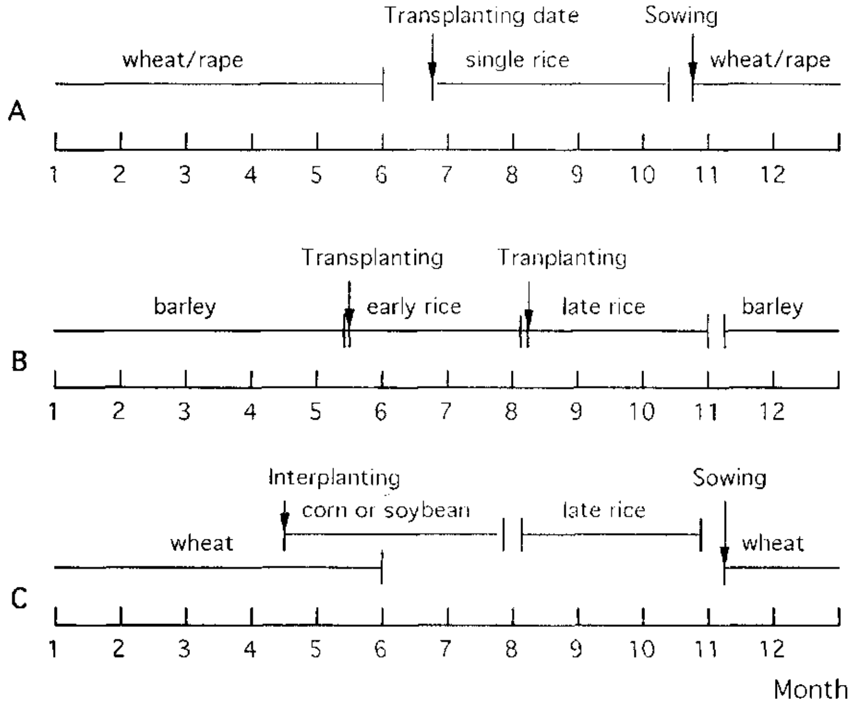

Figure 1. Three cropping systems in Danyang County, Jiangsu Province, representing two traditional systems (A and B), and one new cropping system (C).

late rice in summer (Figure 1C).

The objective of our research was to analyse and compare the performance of traditional single and double cropping systems and the recent triple cropping systems in Danyang County. Crop growth simulation modelling was used as a tool to indicate potential crop yields and crop durations of the various crops in the cropping systems. Risk analysis was performed by simulating crop growth for a number of years, and by comparing the simulated crop 'time-frames' with the likelihood of cold-injury in early spring and autumn. Cropping systems are indicated that make optimum use of the climatic resources light and temperature and that give high economic returns.

Material and methods

The crop growth simulation module L1D from the MACROS model (Penning de Vries et al., 1989) for potential production was adapted with data from different grain crops: rice, wheat, barley and corn. Potential production means that the crop is grown under ample supply of water (irrigation) and nutrients and that it is free from pests, diseases and weeds. Thus, potential yield is more or less synonymous with 'climatic yield potential' as mentioned in the Chinese literature.

Special field experiments were conducted for three crops to obtain growth data on e.g.

yield, phenological development and dry matter accumulation: early rice (cv. ZUX126, late maturing Indica), late rice (cv. 9380, Japonica) and corn (cv. SUYU 12, medium maturing variety). Three sowing dates were used for early rice, April 20, 25 and 30, four sowing dates for corn, April 5, 15, 25 and May 5, and two sowing dates for late rice, June 25 and July 5. Ample water and nitrogen, phosphorus and potassium fertilizer were given to all fields. For wheat, barley and single rice, growth data and crop characteristics were taken from experiments carried out by the Danyang Agricultural Bureau, especially from the local highest yield production experiments.

Crop parameters for the simulation model were derived from the above field data, from Chinese literature (Li, 1986; Feng & Xia, 1989), and from Penning de Vries et al. (1982, 1989). Simulation results for early rice are given in Figure 2.

Potential yields and crop durations were simulated for different sowing dates of crops in the following cropping systems: barley-early rice-late rice (B-R-R); wheat interplanted with corn-late rice (W/C-R) and wheat-single rice (W-R). The simulation of rice growth started at transplanting after 30 days seedbed, using a fixed initial state for all sowing dates. In the wheat/corn interplanted simulation, the following processes were taken into account and adapted in the model: the partitioning of assimilates in wheat and corn, and the shade effects on photosynthesis of wheat on corn (during the corn's seedling stage).

Daily weather data to run the simulation model (i.e. maximum and minimum temperature, irradiation derived from sunshine duration hours) were obtained from the Danyang Meteorological Station for five years between 1986 - 1990.

To make a simple cost/profit analysis of the three cropping systems, collected data from farmers' records and from local townships were used.

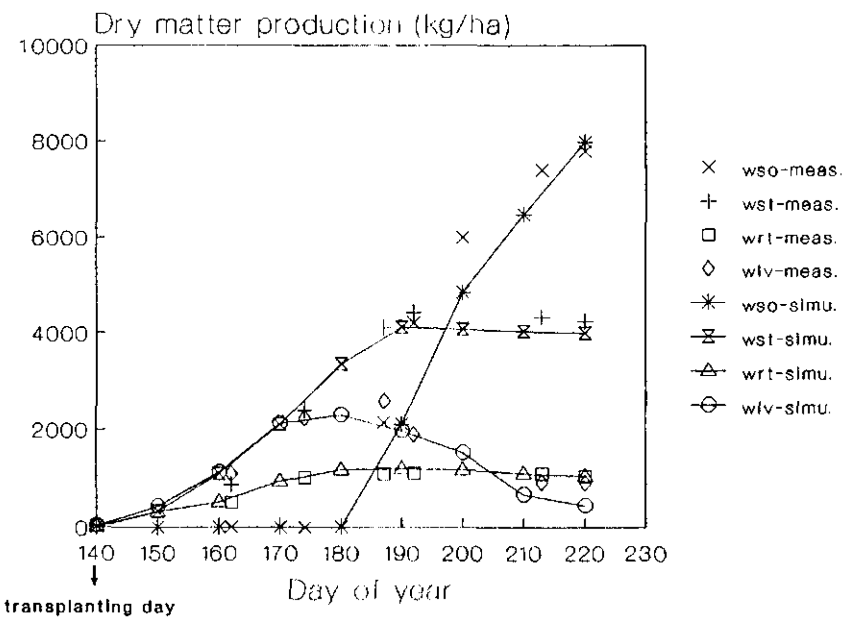

Figure 2. Measured and simulated dry matter accumulation of early rice.

Results and discussion

Growth duration and potential yield of individual crops

The lowest average minimum and maximum daily temperatures, derived from 28 years recording, are about −8.0 °C in January and 38.2 °C in July. In spring, low temperatures often occur at the end of March and the beginning of April. The first date in the season with 80% frequency that (subsequent) daily temperatures are 10 °C or more is April 10. Usually, farmers sow their first rice crop between April 15 - 30 to avoid low temperature effects on germination and early development. Since the crop growth model L1D only starts simulation of rice growth at transplanting, this low temperature effect in the seedbed is not taken into account in the simulation results. In autumn, there is risk of cold injury to the second rice crop during panicle initiation and grain filling. The first date in the season with 80% frequency that (subsequent) daily temperatures are 20 °C or less is September 20. In the model L1D, temperature effects during these late season growth stages are included.

Simulated potential yield of early rice decreased with later transplanting date, i.e. dates 5/10, 5/20, 5/30 and 6/9 (month/day) (Table 1). Similarly, the growth duration decreased with later transplanting date. For instance, when rice is transplanted on May 30, its maturity date is often around August 8. The reason for the decreasing yields and crop durations are the high temperatures in the later growing stages which shorten the period of grain filling. Combining the desirability for early transplanting to obtain high yields, with the 'cut-off' date of April 10 to avoid cold injury in the seedbed, optimum sowing dates of early rice are April 10 - 25 (allowing 30 days seedbed time).

Table 1. Simulated maturity dates and yields of *early* rice with four transplanting dates in Danyang County. Initial variable values at transplanting: Development stage (DSI) = 0.26; Leaf weight (WLVI) = 123 kg ha^{-1}; Weight stem (WSTI) = 121 kg ha^{-1}. Seedling age was 30 days.

Year	Transplanting date (month/day)							
	5/10	5/20	5/30	6/9	5/10	5/20	5/30	6/9
	Maturity date (month/day)				Yield (kg ha^{-1})			
1986	7/28	8/1	8/6	8/11	7288.0	7173.9	7145.5	7109.8
1987	7/29	8/2	8/10	8/14	7436.8	7196.4	7233.9	6959.1
1988	7/30	8/3	8/8	8/13	7272.8	7363.4	7452.3	7248.3
1989	7/29	8/4	8/9	8/14	7709.3	7609.0	7452.3	7440.4
1990	7/28	7/31	8/5	8/12	7319.0	7224.5	7351.1	7201.8
Mean					7405.2	7313.4	7384.6	7192.9

Table 2. Simulated maturity dates and yields of *late* rice with four transplanting dates in Danyang County. Initial variable values at transplanting: Development stage (DSI) = 0.49; Leaf weight (WLVI) = 223 kg ha^{-1}; Weight stem (WSTI) = 217 kg ha^{-1}. Seedling age was 30 days.

Year	Transplanting date (month/day)							
	7/30	8/4	8/9	8/14	7/30	8/4	8/9	8/14
	Maturity date (month/day)				Yield (kg ha^{-1})			
1986	10/24	10/30	11/5	11/11	8037.6	7824.3	7604.2	7277.5
1987	10/25	10/31	11/7	11/11	7805.5	7767.8	7516.1	6919.5
1988	10/27	11/3	11/8	11/15	7805.8	7773.5	7445.0	7074.6
1989	10/25	10/31	11/7	11/11	7697.7	7694.3	7416.4	7247.4
1990	10/23	10/30	11/4	11/11	7440.1	7486.3	7299.0	6910.8
Mean					7757.3	7709.2	7456.1	7085.8

Simulated potential yields of late rice (transplanting dates 7/30, 8/4, 8/9 and 8/14) were somewhat higher than those of early rice because the lower temperatures in the late season resulted in longer growth durations (Table 2). However, potential yield decreased again with later transplanting dates, because of cold-injury during grain filling. Cold injury started when transplanting was later than August 4. From the simulation results we can conclude that early transplanting of the late rice crop results in the highest yields. Therefore, the first season crops (such as early rice, corn) should be harvested before the end of July.

Simulated potential yields and crop durations of corn are given in Table 3. The potential yield was relatively stable with sowing date (dates 4/10, 4/15, 4/20 and 4/25), with a slightly decreasing trend with later sowing. When corn was sown before April 20, its maturity date was generally at the end of July, which is just in time to establish an early, high yielding late rice crop (see above). Considering the cut-off date of April 10 to avoid possible cold injury, the best sowing date for corn is between April 10 and 25.

Growth duration and potential yield of cropping systems

The double and triple cropping systems in Danyang County are bound by the total effective temperature sum and by the course in daily temperature during the year. The choice of individual crops and crop sequences is restricted by the sowing (or transplanting) and harvest dates that limit the risk for cold injury and that allow sufficient time to complete the crop growth cycles. From the analysis of 'single' crop performances, the following sowing and transplanting dates were selected for the three cropping systems under consideration: early rice transplanting date on May 25, late rice transplanting date on August 4, single

Table 3. Simulated maturity dates and yields of corn with four sowing dates in Danyang County. Initial variable values at sowing: Development stage (DSI) = 0.36 Leaf weight (WLVI) = 30 kg ha^{-1}; Weight stem (WSTI) = 10 kg ha^{-1}. Sowing density was 4500 plants per mu; 1 ha = 15 mu.

Year	Sowing date (month/day) 4/10	4/15	4/20	4/25	4/10	4/15	4/20	4/25
	Maturity date (month/day)				Yield (kg ha^{-1})			
1986	7/25	7/27	7/30	8/2	7918.3	7857.1	7908.1	7822.7
1987	8/2	8/3	8/4	8/6	7918.0	7920.6	7978.9	7863.9
1988	7/25	7/28	7/30	8/5	8063.6	8118.0	7966.6	8090.8
1989	7/28	7/31	8/2	8/5	8321.6	8351.7	8322.2	8260.2
1990	7/25	7/26	7/29	8/1	8531.8	8445.5	8330.9	8338.3
Mean					8150.7	8138.6	8101.3	8075.2

rice transplanting date on June 20, corn sowing date on April 15. In the triple cropping systems, the sowing dates of (winter) wheat and (winter) barley were November 4, and in the double cropping system, the sowing date of wheat was October 25.

With the above sowing and transplanting dates, the maturity dates of each crop in the three cropping systems were simulated and are given in Table 4. In the B-R-R cropping system, the maturity date of barley exceeded the suitable transplanting period for early rice of April 10 - 25 in two out of the five years. The 'climatic risk' for this cropping sequence was therefore 40%. Considering that there is also time needed for harvesting, land preparation and sowing, the risk will even be higher than 40%. The maturity date of the early rice, in its turn was always close to the transplanting date for the late rice crop. In two out of the five years, the maturity date was later than August 4, so the risk of the late rice crop suffering from cold injury was 40% (again, not even taking into account the time needed for management). These simulation results agree with observations from many years of field experimentation done by other researchers in Jiangsu Province (e.g. Lu & Shi, 1983).

In the W/C-R cropping system, the maturity date of corn was always at the end of July, about one week before the transplanting date of early rice. The maturity date of corn was 5 - 7 days more favourable for timely transplanting of a late rice crop than the maturity date of early rice in the B-R-R cropping system. Without taking the time needed for management activities into account, the risk of this cropping sequence was 0%, and climatic suitability was 100% .

In the W-R cropping system, there was about 3 - 4 weeks time between the maturity

Table 4. Simulated maturity dates of the crops in the three multiple cropping systems in 5 years in Danyang County. The cropping systems are: W/C-R = wheat/interplanted corn-late rice; B-R-R = barley-early rice-late rice; W-R = wheat-single rice.

Year	W/C-R Wheat Corn Rice	B-R-R Barley Rice Rice	W-R Wheat Rice
1985--86	5/30 -- 7/27 --10/29	5/25 -- 8/4 -- 10/29	5/29 -- 10/11
1986--87	6/10 -- 8/1 -- 10/29	6/2 -- 8/6 -- 10/29	6/10 -- 10/13
1987--88	6/3 -- 7/28 --11/1	5/28 -- 8/3 -- 10/31	6/2 -- 10/14
1988--89	5/28 -- 7/31 --11/2	5/25 -- 8/5 -- 10/29	5/28 -- 10/13
1989--90	5/29 -- 7/27 --10/28	5/22 -- 8/2 -- 10/26	5/27 -- 10/9

date of wheat and the transplanting date of single rice. In this period, the land is left without crop, which means that light and temperature resources are not being utilized for crop production.

Table 5 summarizes the potential grain yields of the three cropping systems. The total potential yield of the B-R-R system was highest, immediately followed by the yield of the W/C-R system which was lower by only 1250 kg ha^{-1} on the average. The double cropping W-R system had the lowest total yield, about 4500 - 5850 kg ha^{-1} less than the triple cropping systems. The yield sequence of the individual crops of the three cropping systems were single rice > late rice > early rice > wheat (double cropping) > corn/barley > wheat (triple cropping). The interplanted corn yielded about 2000 kg ha^{-1} less than when corn was

Table 5. Simulated potential yields (kg ha^{-1}) of crops in three multiple cropping systems in 5 years in Danyang County. The cropping systems are: W/C-R = wheat/interplanted corn-late rice; B-R-R = barley-early rice-late rice; W-R = wheat-single rice.

Year	W/C-R Wheat Corn Rice	B-R-R Barley Rice Rice	W-R Wheat Rice
1985--86	6221.6--6126.9--7986.1	6660.6--7410.2--7804.7	7589.4--8886.6
1986--87	5775.8--6002.5--7864.6	6116.2--7461.4--7837.6	6996.8--8816.9
1987--88	6000.8--6898.6--7900.4	6165.1--7421.4--7622.2	7116.3--8815.9
1988--89	6169.3--6748.8--8145.1	6345.1--7731.1--7765.2	7288.9--8225.6
1989--90	5994.7--6423.0--7558.2	6826.2--7498.9--7529.4	7048.5--8082.2
Mean	6032.8--6439.9--7890.8	6422.6--7484.7--7711.6	7207.9--8565.4
Mean sum	20363.5	21618.9	15773.3

planted as a single crop (Table 3), which is due to the shading by the wheat crop. Similarly, the wheat yield in the W-R system is 1200 kg ha^{-1} higher than in the intercropped W/C-R system because of 'sharing' the light resource with corn in the intercropped system, and because of a slightly longer growth duration in the W-R system. Wheat was not suitable to combine with two rice crops (early and late) into a triple cropping system because the late maturity date of wheat would lead to delays in the transplanting dates of the rice crops, which would result in low rice yields.

Comparison with actual situation

The actual yield of single rice in Danyang County can reach relatively high levels in some situations (7519 kg ha^{-1} reported), showing an agreement with simulated potential values. The reported actual yields for wheat, barley and corn average some 4395, 3290 and 5908 kg ha^{-1}, respectively. So, there is a large gap between actual and simulated potential yield, especially for wheat and barley. Waterlogging has been shown to be an important yield-reducing factor for these crops (Xun & Xu, 1980). To raise current actual yields, soil water drainage condition should be improved (to lower the soil water table) and soil fertility should be increased.

Average actual costs and net profits for the three investigated cropping systems are summarized in Table 6. The production costs of the triple cropping systems are much higher than that of the double cropping system. Though the costs of the B-R-R system are only slightly higher than that of the W/C-R system, its net profit is much lower (despite the highest simulated total grain yield). The net profit of the B-R-R system is even much lower than that of the double cropping W-R system. The highest net profit is realized with the W/C-R triple cropping system. As a result, the B-R-R cropping areas have declined in recent years and farmers have selected new cropping systems with high grain yields, less time and labour input and better economic returns, such as the wheat(barley)/corn (soybean) -late rice system.

Conclusions

Simulation results showed that 'barley-early rice-late rice (B-R-R)' and 'wheat-interplanted corn-late rice (W/C-R)' triple cropping systems have a high total potential grain yield (20000 - 21000 kg ha^{-1}) compared to that of a W-R double cropping system (about 16000 kg ha^{-1}). However, the B-R-R system had a high risk of delayed transplanting of the early and late rice crops, leading to reduced yield of the early rice crop because of short crop durations, and to reduced yield of the late rice crop because of cold injury. Moreover, there is very little time available between the harvest of a preceding, and the transplanting of a succeeding crop, which leads to timing and labour problems. Currently in Danyang County, net profits of the B-R-R triple cropping system are also very low, so that farmers select new cropping systems. The W/C-R triple cropping system had less risk of delayed transplanting of succeeding crops, and combines high total potential grain yield with high economic

Table 6. General costs and net profits (in yuan ha^{-1}) of the three cropping systems in Danyang County. The cropping systems are: W/C-R = wheat/interplanted corn-late rice; B-R-R = barley-early rice-late rice; W-R = wheat-single rice.

Cropping system	Costs	Net profits
W/C-R	7871.2	6967.8
B-R-R	7990.5	5289.2
W-R	5675.4	6313.9

returns in practice. Therefore, we recommend a triple cropping system in Danyang County, in which winter crops can be interplanted by corn (or others such as soybean) in spring, and followed by late rice afterwards. This area should account for about 25 - 33% of the total cropped area, considering the ratio net profit/costs between the W/C-R and the W-R systems.

The next step in simulation modelling should be the inclusion of the effects of waterlogging on crop growth and development of wheat, barley and corn.

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Temporal and spatial changes of microclimate in paulownia-wheat intercropping systems

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Abstract

The effect of paulownia-wheat intercropping on microclimatic variables and on wheat growth was studied using 10 years of experimental data on 6, 10, 20, 30, 40 and 50 m tree spacing trials. Compared with a control field, total solar radiation in dense tree spacings was significantly decreased, but slightly decreased in larger spacings, 8 - 4% at 40 and 50 m spacing, respectively. Average reflected radiation increased at 6 - 20 m spacing, and decreased at 40 and 50 m spacing. Daytime air temperature decreased with about 0.2 - 1.5 °C at 6 to 20 m spacings, but increased with 0.4 °C at the 40 m spacing. Night air temperature increased at any tree spacing. Vertical temperature inversion appeared during daytime under tree crowns. Wind speed and evaporation decreased some 27 - 58% and 30 - 65%, respectively. Average soil moisture increased with about 16 - 31%. Maximum soil temperature was reduced by 3 - 11 °C and minimum soil temperature increased by 0 - 4 °C. Intercropping sometimes increased relative air humidity. The air moisture content at the crop layer was higher than at upper layers.

After about four years of intercropping, wheat yields declined relative to single cropped wheat yield at 6 to 20 m tree spacings, but moderately increased at tree spacings larger than 20 m. After ten years of intercropping, wheat yields at 30 to 50 m tree spacings were 101 - 105% of single cropped wheat yield. Simulation models can be useful tools to understand the complex interacting between crop growth and microclimate, and to transfer experimental results to different agro-ecological environments.

Introduction

In China, paulownia is an indigenous, very adaptable, extremely fast growing and multi-purpose tree. Its wood is light but strong and suitable for the manufacture of a.o. furniture, plywood and musical instruments. The leaves and flowers are desirable sources of fodder and green manure as they contain not only the eight essential amino acids but are also rich in nutrients and micro-elements. Paulownia is considered as the most promising tree species for intercropping; to date, about 2 million hectares of farmland are used for intercropping of paulownia with wheat, corn, cotton, tea and medicinal or cash crops. The most common paulownia species used for intercropping is *Paulownia elongata* S.Y. Hu, and the most suitable intercrops are spring wheat and winter wheat. Paulownia's branches and leaf arrangement are sparse with late leaf emergence (beginning of May) and late leaf fall (end of November). The sparse crown allows a large amount of light to pass through which is thus available for absorption by the intercropped wheat at any time. The late leaf fall favours the protection of wheat from cold in the winter (Zhu et al., 1978; 1985).

The modification of the microclimate in paulownia-wheat intercropping systems and the effects on the intercropped wheat yields have been widely studied in China (Zhu et al., 1978; 1985). However, the spatial and temporal changes of microclimate under specific tree densities and at different crop growth stages have not received any attention in most studies, and is the topic of this paper. The effect of microclimate in different paulownia spacings on wheat growth and yield at various growth stage combinations of both paulownia and wheat is presented in order to provide benchmark information on yield and economic output per unit land. Moreover, the data presented here will be useful in building simulation models of paulownia-wheat intercropping systems.

Material and methods

Field experiments were conducted at the Dangshan Paulownia Research Station, Anhui Province, Peoples Republic of China. The temperate monsoon climate has a mean annual rainfall of 773 mm with almost 80% occurring during the rainy season (July - Sept). The mean daily air temperature is 14.0 °C with minimums varying between −10 and −15 °C. The soil is alluvial, sandy and alkaline. Late spring and early summer (March - May) often have hot and dry winds (speeds > 3 m s^{-1}) with temperatures over 30 °C and a relative humidity of less than 30%. These conditions are extremely harmful to agricultural crops, especially wheat, and result in yield losses of up to 20 - 40%. Wheat is sown at the end of October and harvested in the first week of June.

Five different row spacings of paulownia-wheat were studied, 6, 10, 20, 40 and 50 m. The tree spacing within the rows was 5 m. The experiments were started with 1-year-old saplings in 1983. All rows were north-south oriented. Randomized Complete Block Design (RCBD) with three blocks (replicates) were used for each spacing treatment. In the 8th year of intercropping, spacings of 6 and 10 m were thinned into 30 m. Table 1 summarizes the condition of the paulownia trees in each spacing in the different ages of plantation. Winter wheat was continuously intercropped each year from tree planting onwards. For comparison, a control plot of the same variety of winter wheat was grown in a nearby open field. All plots did not receive any irrigation during the entire growing season.

Data were collected during10 years of experimentation. Most (though not all, see Table 1) data used in this study were collected at the 7th intercropping year. The microclimatic factors solar radiation, wind velocity, wet and dry bulb temperature and soil temperature were recorded hourly for 3 - 4 days, with at least one day having continuous 24-hour data collection, at each growth stage. The sensors for air and soil temperature were installed at

Table 1. Height (H), diameter at breast height (DBH), crown width in north-south direction (CWNS) and in east-west direction (CWEW), and closure coefficient of paulownia trees at different row spacings and at different ages. The tree spacing within the rows was 5 m.

Spacing (m)	Age (years)	H (m)	DBH (m)	CWNS (m)	CWEW (m)	Closure (-)	Year
6	5	9.0	0.15	6.0	5.5	-	1986
6	8	12.0	0.22	6.3	5.7	0.87	1989
10	5	9.0	0.15	6.1	5.5	-	1986
10	8	12.1	0.25	6.5	5.5	0.58	1989
20	8	11.8	0.26	6.6	5.6	0.29	1989
30	12	15.0	0.36	9.0	6.0	-	1986
40	8	8.4	0.21	6.0	5.2	0.13	1989
50	8	8.9	0.22	5.9	5.5	0.1	1989

the centre of the control plot: at 2, 5 and 8 m from the western tree row for the spacing of 10 m; at 3 m for the 6 m spacing; at 2, 10 and 18 m for the 20 m spacing; at 2, 11 and 20 m for the 40 m spacing; and at 2, 13 and 25 m for the 50 m spacing. The incoming (Rs) and reflected (Rr) solar radiation over each plot were measured as hourly integrated values using an Automatic Recording Radiation Station at 10 cm above the wheat canopy. Wind speed was measured at 2 m height above ground with 3-cup anemometers connected to Automatic Wind Stations; dry and wet bulb temperatures were collected using Ventilating Wet-Dry Thermometers at two elevations, at 10 cm above the wheat crop (Z1) and 1 m heigher than Z1 (Z2). Soil temperature was measured hourly by curved thermometers at 0, 5, 10, 15, 20 and 40 cm depths. Maximum and minimum soil surface temperatures were measured by maximum and minimum thermometers. The soil moisture content was determined gravimetrically using samples from 10 cm layers, 0 - 40 cm below the soil surface.

Intercropped winter wheat parameters such as Leaf Area Index (LAI), 1000-grain weight, above-ground biomass and wheat yield were collected in three replicates in each sample strip at a standard distance from the paulownia rows. Fifteen samples of wheat were taken from the control field (monoculture). The LAI was measured at each growth stage.

Results and discussion

Shading

Shading was found to be a key factor affecting microclimatic variables in the intercropped plots. The shaded area was negatively related to solar declination (angle with respect to the horizontal plane) and positively related to the distance from the trees. Shading periods

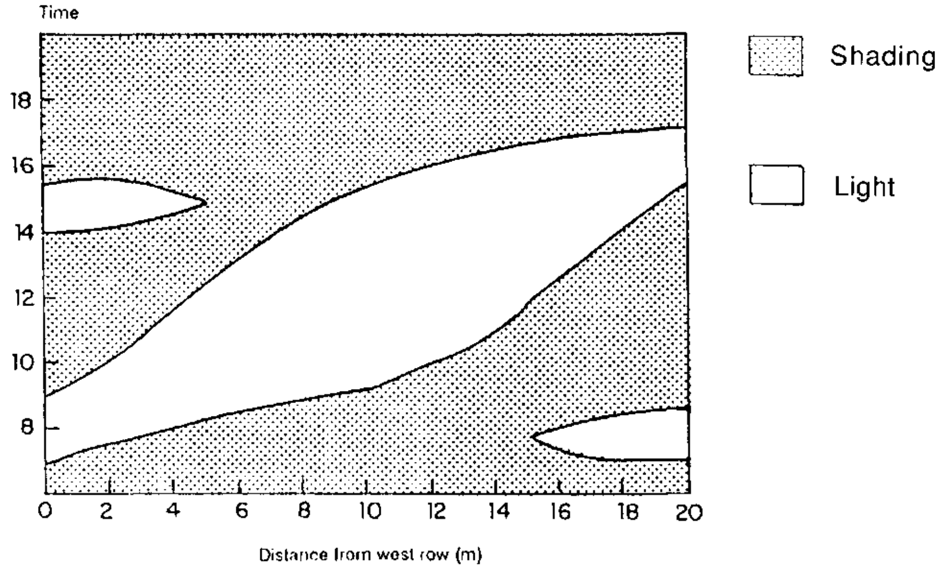

Figure 1. The movement of shade from paulownia trees between two tree rows at 20 m spacing, 17 May 1989 (7th intercropping year).

continued longer as the shaded area was closer to the tree rows. As shown in Figure 1 for the 20 m spacing plot, most of the space between two tree rows were shaded before 7:00 a.m. The shaded area moved from west to east with increasing solar declination and was smallest at noon when solar declination was highest. At 2 m from the western row, exposure to direct sunlight was between 7:30 and 10:00 a.m., at 5 m between 8:30 a.m. and 12:30 p.m. and at 10 m (middle between the trees), between 9:30 a.m. and 3:00 p.m. In addition, sunlight would penetrate through the tree crowns at 2 m from the western tree row during 3:30 to 5:00 p.m. The sunlight exposure time was slightly longer in the western part of the plot than in the eastern part, though the sunlight's appearing time was opposite. At 15 m from the western tree row (5 m from the eastern row) exposure to direct sunlight was between 12:30 and 4:30 p.m., and at 18 m between 1:30 and 4:30 p.m. and between 7:30 and 9:00 a.m.

The shading pattern varied with paulownia densities. The area between the trees was shaded nearly throughout the day at 6 m spacing and only received sunlight that penetrated through the sparse tree crowns. At 10 m spacing, there were only 2 - 3 hours of direct sunlight exposure between the tree rows. The proportion of illuminated area at 40 m spacing increased drastically compared to that in dense spacings. Exposure to sunlight could last 8 - 9 hours in the area 10 - 30 m from the western tree rows.

The shaded area was also positively related to tree height and/or age. With the same spacing, shaded areas increased with height/age of the trees. The shading intensity depended on the density of the tree crowns. There were more scattered sunlight patches during flowering of paulownia than when the leaves were fully developed.

Solar radiation

The wheat crops in the intercropped plots received less solar radiation than the crop in the control plot. Reduction of solar radiation depended on paulownia spacing and growth stage. The reduction of solar radiation was larger in denser paulownia spacings and after the paulownia leaves were fully developed. Compared to the control plot, total solar radiation was 27.8, 25.3 and 0.33% lower during April at the 10, 20 and 50 m spacings, respectively, and 81.9, 65.8, 30.0, 7.6 and 3.9% lower during May at the 6, 10, 20, 40 and 50 m spacings, respectively.

The study also suggested that the effects of paulownia on the reduction of solar radiation on the wheat canopy also depended on tree age. The average total solar radiation at 10 m spacing after 4, 5, 6, 7 and 8 years were 98.2, 98.0, 67.9, 55.6 and 34.2% respectively of that in the control plot. Earlier effect on radiation reduction was observed in denser spacings. For instance, at 6 and 10 m spacing, solar radiation was not significantly affected when the trees were younger than 5 years (or fourth intercropping year) but after the fourth intercropping year, solar radiation was significantly reduced. On the other hand, radiation was only slightly reduced between the tree rows at the 7th intercropping year at 40 m spacing.

Total solar radiation between the paulownia rows varied with distance from the tree rows. The amount of radiation received by the wheat canopy increased with increasing distance from the trees. The distribution of total radiation between two tree rows was almost normal (Figure 2), with the area 2 m away from the eastern row receiving 9.4% more radiation than the area 2 m away from the western row. This phenomenon occurred in most cases over long periods. This might be due to the fact that the exposure to sunlight lasted slightly longer near the western tree rows than near the eastern tree rows.

The hourly pattern of solar radiation in the control plot and at 20 m spacing is given in Figure 3. In the middle between the tree rows, the pattern was the same as that in the control and the radiation difference was smallest between 10 a.m. and 3 p.m. (due to shading before 10 a.m. and after 3 p.m.). At 2 m distance from the western row and from the

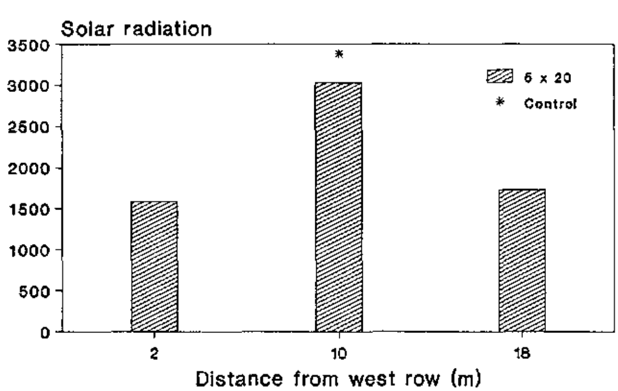

Figure 2. Total solar radiation as function of distance from the western tree row at 20 m tree spacing (17 May 1989), and in the control wheat field (no trees).

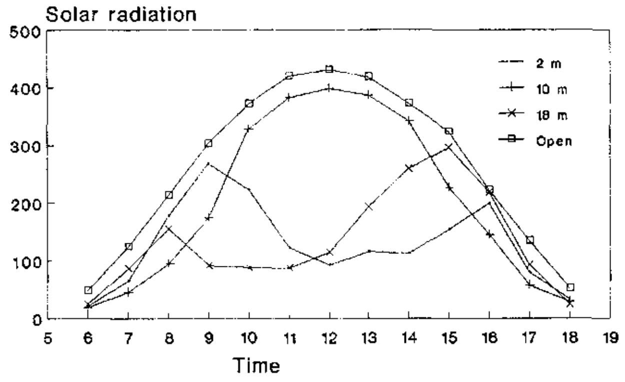

Figure 3. Hourly solar radiation versus time at three distances from the western tree row at 20 m tree spacing, and in the control wheat field.

eastern row, radiation peaks coincided with the sunshine exposure hours. The smaller peaks occurred when sunlight penetrated the tree crown and the higher peaks appeared when there was no shading. Radiation varied with distance and was more apparent in denser spacings than in open ones.

Average reflected radiation (Rr) increased in the denser intercropped plots but decreased at 40 and 50 m spacings. Reflected radiation at the centre of the plots in May was 23.1, 19.1, 16.2, 12.0, and 12.7% at 6, 10, 20, 40 and 50 m spacing, respectively. It was 158.1, 136.2, 101.9, 78.7 and 97.9% respectively of that of the control plot. Reflected radiation was negatively related to air temperature as described by Rosenberg (1983).

Wind speed

Reduction in wind speed differed with paulownia growth stage. With four year old trees, wind speed at 10 m spacing was reduced by 25.8 - 30.0% during paulownia's dormancy stage in December. Reduction was higher by 32.9 - 38.1% during the flowering stage towards the end of April. A further reduction by 35.0 - 40.1% was observed when the leaves were fully developed in early June. With eight year old trees, wind speed at 20 m spacing was reduced in average by 41.0% and 58.2%, in the middle of April and May, respectively.

Wind speed was more reduced with denser tree spacing (Table 2). The average wind speed between paulownia rows during May decreased by 45.2, 58.2, 41.6, 22.4 and 27.0% at 6, 10, 20, 40 and 50 m spacing, respectively, compared to that in the control plot. The reduction in wind speed depended on wind direction and distance from the tree rows. The reduction in wind speed was smallest going from one tree row to another in leeward direction and was larger toward windward direction (Figure 4).

Air temperature

The paulownia trees had a non-consistent effect on air temperature. Generally, tree crowns act as a barrier against heat transfer and reduce air mixing and evaporation, resulting in increased air temperature (Rosenberg, 1983). However, in this study, shading and the

Table 2. Wind speed at different spacings and ages of paulownia trees rows, and at the control field.

Date	Spacing (m)	Age (year)	Wind speed (km d^{-1})		
			Intercropped	Control	Intercropped/Control (%)
1-3/6	10	3	80.0	110.0	27.2
10-13/5	6	4	116.0	153.5	24.4
26-28/5	10	4	111.0	179.0	38.0
4-6/5	20	4	86.3	101.7	15.1
1-3/6	10	6	50.0	95.0	50.0
29-31/5	6	7	60.4	110.2	45.2
20-23/5	10	7	83.5	199.7	58.2
15-18/5	20	7	161.9	277.2	41.6
26-28/5	40	7	141.3	182.0	22.4
19-21/5	50	7	62.9	86.2	27.0

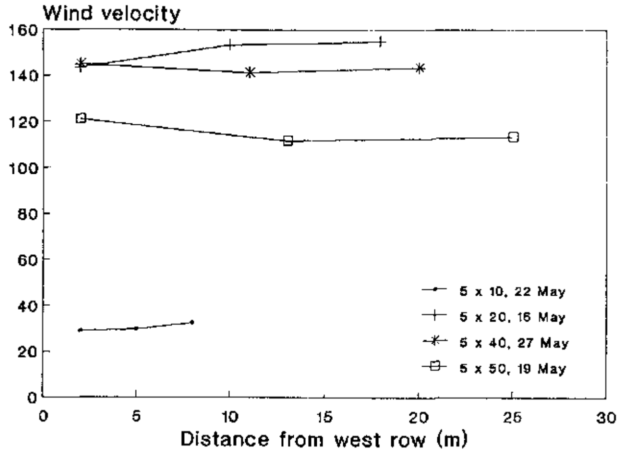

Figure 4. Wind speed as function of distance from the western tree row at 10, 20, 40 and 50 m tree spacing (16 - 22 May 1989).

consequent reduction in irradiation often led to decreased air temperatures. During the first five intercropping years, air temperature in denser paulownia spacings, e.g. at 6 and 10 m spacing, was higher than that in the control plot. But later, after the 6th intercropping year, air temperatures were lower than in the control plot. This non-consistent temperature effect was due to the fact that shading and reduction in radiation were not significant in the first few years when the trees were young. Shading became significant in later years with increasing tree closure. At the larger spacings, the air temperature was higher than in the control plot except in the areas under the tree crowns. The average daytime air temperature between the tree rows at 6 m spacing with 3, 4, 5, 6 and 7-year-old trees in May were respectively 0.2, 0.45, 0.79, 0.7 and 0.12 °C higher than in the control plot. However, air temperature started decreasing at 6, 10 and 20 m spacing at the 7th intercropping year. The average daytime air temperature at 6, 10 and 20 m spacing was respectively 0.6 - 2.3, 0.2 - 1.5 and 0.4 °C lower than in the control plot at two measuring stages. At 40 m spacing, the average daytime temperature was 0.4 °C higher than in the control plot, but at 50 m spacing, there was hardly any difference in daytime temperature.

Daytime air temperature also varied with distance from the paulownia rows (Figure 5). It was highest in the middle of the rows and decreased towards the trees at all spacings. The temperature was slightly higher at 2 m from the western row than at 2 m from the eastern row in the morning, and slightly lower in the afternoon, due to shading effects. The relationship between temperature and distance from the tree rows was more obvious on

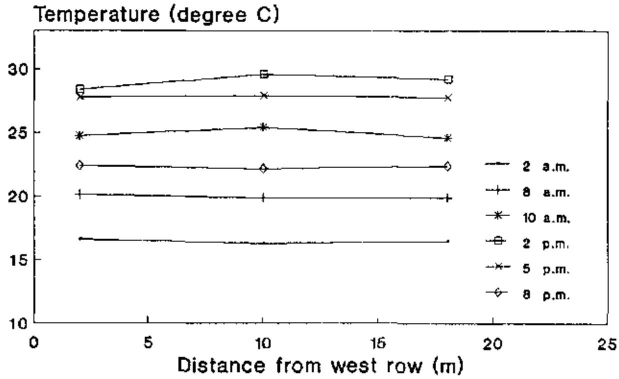

Figure 5. Air temperature as function of distance from the western tree row at 20 m tree spacing, at six times during the day/night (17 May 1989).

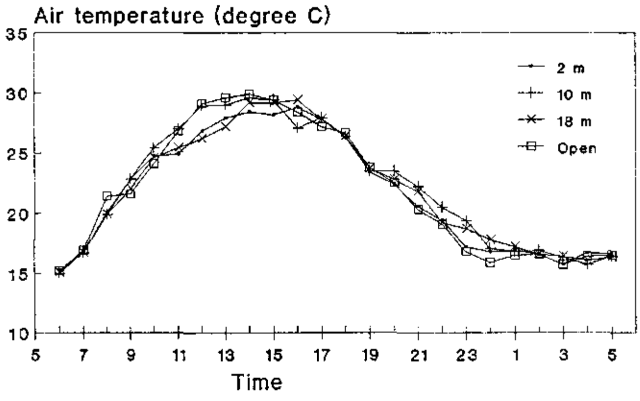

Figure 6. Air temperature versus time at three distances from the western tree row at 20 m tree spacing, and at the control wheat field (17 May 1989).

clear days than on cloudy days, and in the wider spacings than in the denser spacings, especially at noon (Figure 6). On clear days in May at the 7th intercropping year, the air temperature at 10, 20, 40 and 50 m spacing was respectively 0.13, 0.1 - 0.8, 0.3 - 0.8 and 0.3 - 0.8 °C higher in the middle than that at 2 m from the tree rows.

Night air temperature increased by 0.1 - 1.0 °C over the control at any distance from the paulownia rows and at any spacing. However, the relation between air temperature at night and distance from the tree rows was opposite to that at daytime. The further away from the tree rows, the lower was the air temperature (Figures 5 and 6).

Temperature inversion usually took place earlier and was more intense at night, with lapse rate occurring at shorter duration during the day, in the intercropped situation than in the control plot (Figure 7). However, the vertical temperature profile under tree crowns was not so regular, that is, inversion occurred during daytime. The denser the spacing and the nearer the area to the trees, the longer and more intense and/or more frequent was the temperature inversion. Usually, no lapse developed at daytime with the 6 m spacing. The stable situation only appeared at 12:00 noon with the 6 m spacing, which might have been due to the effect of paulownia shading and crown barrier.

Relative humidity and water pressure

The relative humidity (RH) was up to 9% higher in the intercropped plots than in the control plot. It was slightly higher during clear days, and slightly higher or the same at night. This may be attributed to the combined effects of reduced evaporation and the obstruction caused by the tree barriers.

At 2 m distance from the western tree rows, the RH was lower than the RH in the middle between the rows in the morning, higher in the afternoon and about the same during the night (Figure 8). At 2 m distance from the eastern tree rows, the RH was higher than the RH in the middle during the evening, and about the same during the night and the day.

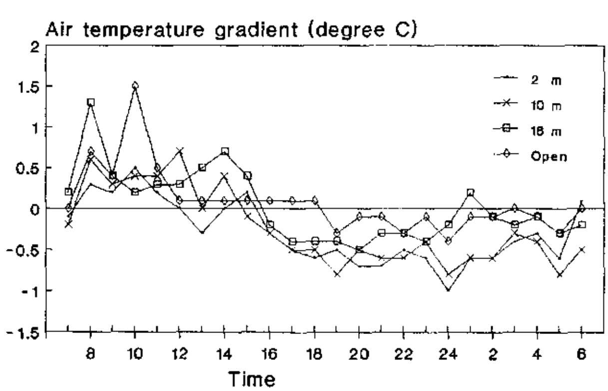

Figure 7. Air temperature gradient (T1-T2) versus time at three distances from the western tree row at 20 m tree spacing, and at the control wheat field (25 April 1989).

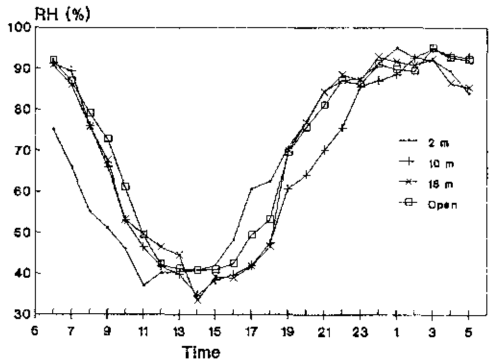

Figure 8. Relative humidity versus time at three distances from the western tree row at 20 m tree spacing, and at the control wheat field (17 May 1989).

During the day, the RH in the middle between the trees was lower than at the control plot, especially in the afternoon and evening. These temporal patterns of RH were more pronounced after the paulownia leaves were fully developed than during flowering and in the older stages. On cloudy and droughty days, only small differences were observed between the RH at different distances from the rows, and between RH at the intercropped and at the control plot.

The vertical water pressure difference was larger in the intercropped plots than in the control plot (Figure 9). The water pressure of the air above the control plot was lower in the upper (air) layer than in the lower (wheat canopy) layer so that the water pressure gradient (X1 - X2) was negative. In the intercropped area, the water pressure gradient (X1 - X2) was positive at any distance from the trees, i.e. the water pressure was higher in lower layers than in upper layers. The magnitude of this positive pressure gradient varied relatively largely close to the trees. At night, the vertical water pressure gradient was nearly zero in the control plot and at any distance from the trees in the intercropped plots.

Soil temperature and soil moisture

The amplitude of soil temperature was smaller in the intercropped fields than in the control plot, at any paulownia density. The average maximum temperature of the soil surface at 2 m from the tree rows was 11 °C lower than in the control plot. In the middle between the trees, it was 9.1, 7.8, 3.2 and 5.1 °C lower at respectively 10, 20, 40 and 50 m spacings. The average minimum temperature at the soil surface was 0.1 - 4.4 °C higher at these spacings. The effect of paulownia in decreasing the soil surface temperature amplitude was greater at areas close to the tree rows, at denser tree spacings, with older trees, and in the seasons when the leaves were fully developed. The average soil temperature in the 0 - 40 cm soil layer was 0.2 - 3.1 °C lower during the day in the intercropped plots than in the control plot, with small difference between the tree spacings. The average soil temperature

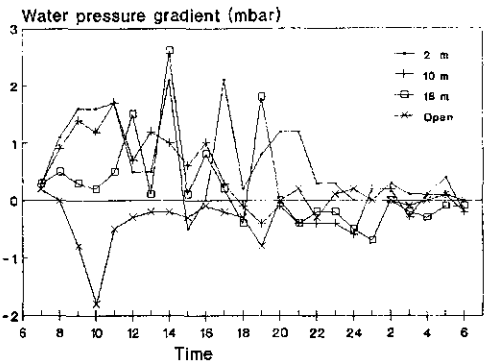

Figure 9. Water pressure gradient of the air (X1 - X2) versus time at three distances from the western tree row at 20 m tree spacing, and at the control wheat field (17 May 1989).

was higher at the middle between the tree rows than near the rows during the day (Table 3). During the night, soil temperature was higher in the intercropped fields than in the control field, and was lower in the middle than near the trees.

Soil moisture was higher in the intercropped fields than in the control field. The average soil moisture in the 0 - 40 cm soil layer was 27.9, 31.2, 22.2 and 15.8% higher in the 6, 10, 20 and 40 m spacing respectively, than in the control plot. The increased soil moisture in this layer could be beneficial to wheat growth since the total amount of water taken up by the crop comes for 50 - 60% from the 0 - 30 cm layer (Doorenbos & Kassam, 1979).

Table 3. Soil temperature at 0 - 40 cm depth in the 7th intercropping year at different spacings of paulownia tree rows, and in the control wheat field (monoculture). Measurements in the intercropped fields were taken at 2 m from the east paulownia row (E2), at 2 m from the west row (W2) and in the middle between the tree rows (M).

Date	Spacing (m)	Soil temperature (°C) E2	M	W2	Control
29/5	6	19.9	-	-	25.0
27/4	10	18.6	18.6	18.1	18.8
25/5	10	18.0	18.4	17.6	22.4
24/4	20	15.7	16.4	16.0	17.7
17/5	20	18.0	19.5	18.1	22.3
28/5	40	20.2	21.8	21.8[d]	23.8
29/4	50	16.2	16.9	16.9[e]	17.2
19/5	50	20.0	21.9	21.9[e]	22.4

[d] At 11 m from western row. [e] At 13 m from western row.

Table 4. Leaf Area Index (LAI, $m^2 m^{-2}$) of intercropped wheat at heading and at grain filling at different spacings of the paulownia tree rows in the 10th intercropping year, and LAI of the control wheat field. In the intercropped fields, measurements were taken under the trees (A), under the edge of the tree crowns (B) and in the middle between the tree rows (C).

Spacing	Heading			Grain filling		
(m)	A	B	C	A	B	C
20	3.2	4.3	4.9	0.13	0.26	0.28
30	3.2	3.5	4.4	0.13	0.73	1.52
40	2.7	3 9	3.7	1.11	0.81	1.2
50	-	-	-	1.08	1.57	0.93
Control	-	-	3.6	-	-	0.48

All the above mentioned modifications of the microclimate with paulownia intercropping were less pronounced at the flowering stage than when the paulownia leaves were fully developed.

Intercropped wheat growth and yield

The modification of the microclimate with paulownia-wheat intercropping at spacings larger than 30 m was favourable for the growth of wheat during the heading and flowering stages. With closer tree spacings, wheat growth was negatively affected, particularly during the grain filling stage which coincided with the full leaf development of the paulownia trees.

Depending on tree spacing and on location in the intercropped field, the LAI of wheat could increase up to 36% in the heading stage and up to 53 - 229% in the grain filling stage (relative to the LAI of wheat in the control field) (Table 4). Only under the trees, the LAI was lower than in the control field during heading at all spacings, and during grain filling at spacings smaller than 40 m. This general beneficial effect of intercropping on LAI was because wheat in the control field sometimes suffered from hot and dry winds during the grain filling stage, which caused the leaves to wither and die. At the larger spacings, 30 - 50 m, total above-ground wheat biomass at grain filling was also larger than in the control field (Table 5). In the10th year of intercropping, total wheat biomass at grain filling increased by 0, 4.6, 27.9 and 26.9%, and ear weight by 0.5, 4.6, 3.8 and 0.05% at 20, 30, 40 and 50 m spacings, respectively, over that of the control field.

The intercropped wheat yield varied with tree spacing, tree age and distance from the tree rows. With 6 and 10 m spacing, there was hardly any effect on wheat yield during the first three years of intercropping (1983 - 1985), but from the fourth year on, wheat yields decreased. With tree spacings larger than 20 m, wheat yield was not affected in the first two years of intercropping, but wheat yield increased from the 3rd year (1986) onwards. Table 6 indicates that the intercropped wheat yields in the 6, 10, 20, 40 and 50 m paulownia spacings were 87.3, 93.7, 105.6 and 106% of those in the control plot at the 4th intercropping year. At the 7th intercropping year, the yield at 6, 10, 20, 40 and 50 m spacing was respectively 52.7, 65.3, 92.8, 106.6 and 112.5% of that of the control plot. At the 9th year, the tree rows in the 6 and 10 m spacing plots were thinned to 30 m spacing. Wheat yield at the 10th intercropping year at 20, 30, 40 and 50 m spacing were 80, 105, 102 and 101% of that of the control field.

Conclusions

The microclimate in paulownia-wheat intercropping systems is largely affected by the presence of the trees. Irradiation, air and soil temperature, wind speed, relative humidity and soil moisture are modified when compared to single wheat (control) fields. The extent of the modification depends on age, density and growth stage of the trees, on the distance from the tree rows, on the time of day and on the weather conditions. The effects were more apparent and significant during clear days, in areas near the paulownia trees, with older paulownia trees, and when the paulownia trees had fully developed leaves.

The modified microclimate affected the growth and final yield of the intercropped wheat. In the first 2 - 3 years of intercropping, wheat yields were the same as single cropped wheat yield at all paulownia spacings (6 - 40 m). From about the fourth year, intercropped wheat yields declined relative to single cropped wheat yield at 6 - 20 m tree spacing, but moderately increased at tree spacings larger than 20 m. After ten years of intercropping, wheat yields were 101 - 105% of single cropped wheat yield. Therefore, the optimum cropping system is: paulownia planting at 20 m spacing and thinning to 40 m at the 7th intercropping year, or planting at 10 m followed by thinning to 30 or 20 m at the 4th intercropping year and to 40 m at the 7th intercropping year.

The transfer of the above recommendation for paulownia-wheat intercropping systems

Table 5. Total above-ground biomass (t ha^{-1}) and percentage biomass of ears, stems and leaves of intercropped wheat at heading and at grain filling at different spacings of the paulownia tree rows in the 10th intercropping year, and of the control wheat field.

Spacing	Heading				Grain filling			
	Biomass	%ear	%stem	%leaf	Biomass	%ear	%stem	%leaf
20	11.48	27	56	17	12.4	66	28	6
30	9.91	27	54	19	12.98	69	26	5
40	10.79	28	56	16	15.86	69	26	5
50	12.35	23	61	16	15.73	66	26	7
Control	11.94	28	53	18	12.4	66	30	4

Table 6. Yield (kg ha^{-1}) of intercropped wheat at different spacings of paulownia trees, and of single cropped wheat in the control field.

Intercropping year	Spacings						
	6	10	20	30	40	50	Control
1st	3045	3086	3090	-	3135	3075	3060
2nd	3290	3263	3375	-	3626	3912	3411
3rd	3752	3794	4302	-	3942	4838	4185
4th	3674	3918	4418	-	4434	4401	4184
5th	2432	3020	3152	-	3753	3653	3459
6th	2366	2784	3158	-	3486	3563	3460
7th	1507	1867	2650	-	3110	3261	2905
10th	cut	cut	3783	4971	4830	4770	4730

to other agro-ecological areas might be hazardous. The effects of the trees on the microclimate, on soil moisture and, consequently, on crop growth are complex and difficult to entangle. In different macroclimates and on different soil types, the effects of tree spacing and tree age on intercropped wheat yield might be different. A useful tool to study these complex interactions and effects could be crop simulation modelling (Penning de Vries et al., 1989; Wu, 1990). The data collected in this study are useful in adapting existing simulation models for monocultures to models that are suitable for intercropping. For instance, the microclimatic variables needed as input in a simulation model for wheat (e.g. radiation, temperature, wind speed, relative air humidity) can be derived from the relationships with macroclimate variables observed in our experiments. Or, these microclimatic variables could be explicitly modelled as function of the tree characteristics (e.g. age, height, spacing, crown density). Simulation work that has been done in the field of competition for resources between crops (and weeds) can be useful in this approach (e.g. de Wit, 1960; Kropff & Spitters, 1991).

Acknowledgments

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Agro-ecology and soils of Tamil Nadu, India

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Abstract

Tamil Nadu is located in the south of India and covers an area of about 13 million ha. The state has been divided into seven agro-climatic zones on the basis of rainfall pattern, altitude and irrigation sources. Detailed investigations on the distribution, characterization and classification of the soils in the state have been carried out. The soils have been classified under six orders of the USDA Soil Taxonomy System: Entisols, Inceptisols, Alfisols, Ultisols, Vertisols and Mollisols. The physical and chemical properties of the soils grouped under the different soil orders are discussed. The soils have been grouped under broad land suitability and land irrigability classes which give constraints when the lands are used for cultivation and sustained irrigation. The presence of hard pans or impermeable layers, and management strategies developed to overcome these constraints for increased agricultural production are discussed.

Tamil Nadu, the physical environment

Location and extent

Tamil Nadu State in India lies between 76° 14' and 80° 21' E longitude and 8° 4' and 13° 54' N latitude. It is bounded on the east by the Bay of Bengal, on the south by the Indian Ocean, on the north by the States of Karnataka and Andhra Pradesh and on the west by the Western Ghats (mountain range) and Kerala State (Figure 1).

Geology

The general geological formations of Tamil Nadu State are:

Recent	- Alluvium
Pleistocene	- Laterite
Mid-Pliocene	- Cuddalore Sandstone
Upper Cretaceous	- Niniyur and Ariyalur formations Tirichirapalli formations Uttatur formations
Mid-Triassic	
Lower Cretaceous	- Upper Gondwanas

Lower Precambrian	- Dharwars super group Khondalite Cale-granulite and Crystalline Limestone
Archean	
Khondalite group	- Quartzite
Charnockite group	- Charnockite Magnitite-quartzite
Intrusives	- Syenite Basic intrusive Granites Ultrabasic intrusives (Dunites, Peridotites)

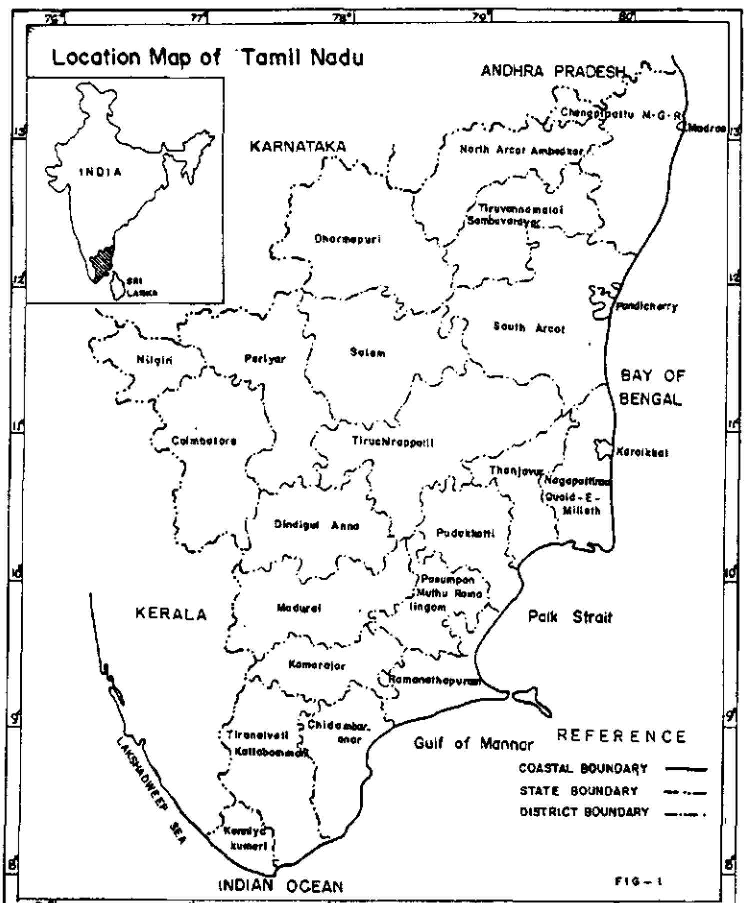

Figure 1. Location map of Tamil Nadu State, India

Geomorphology

Tamil Nadu is divided into four geomorphologic zones, viz. the Coastal plain, the Eastern Ghats, the Central Plateau and the Western Ghats. The Coastal plain stretches from Pulicat lake in the north to Cape Comorin (Kanyakumari) in the south. The Coastal plain is backed by a broken line of hills, viz. The Javadus, Shervaroys, Kalrayans, Pachamalai and Kollimalais. This line of hills is known as the Eastern Ghats. On the western border occurs a group of high hills known as the Western Ghats. They are the Nilgiris, Anamalais, Palanis and Cardamom hills. Between the Eastern and Western Ghats lies the Central Plateau with elevations ranging from 152 to 610 metres above mean sea level. The general topography is undulating with an overall sloping from west to east.

Climate

The climate of Tamil Nadu is a semi-arid tropical monsoon type.

Temperature

The mean annual temperature is 28.2 °C in the plains and 15.2 °C in the hills. The temperature is lowest in December with 24.7 °C and highest in May with 31.3 °C. On the basis of soil temperature, the Coastal Plain is classified as hyperthermic, the Central Plateau as iso-hyperthermic and the Eastern and Western Ghats as isothermic (Hari Eswaran et al., 1990).

Rainfall The mean annual precipitation is 848 mm in the inland plains, 946 mm in the coastal plains and 1666 mm in the hilly regions. The state receives rainfall in two distinct seasons, viz., the south-west monsoon (June to September) and the north-east monsoon (October and December). The winter season lasts from January to February, and the hot summer season from March to May. The average distribution of rainfall in the year is about 46% during the north-east monsoon, 35% during the south-west monsoon, 14% in the summer and 5% in the winter. The soil moisture regime is generally ustic, except in hilly areas where it is udic and in some parts of the south where it is aridic (Hari Eswaran et al., 1990).

Agro-climatic zones

Tamil Nadu is divided into seven agro-climatic zones based on the rainfall pattern, altitude and irrigation source (Table 1; Figure 2).

Land use

The land utilization pattern of the State is given in Table 2. Out of the 5.69 million ha of annual field crops, 44% is irrigated. Wells constitute the main source of irrigation, covering 41% of the net irrigated area in the state, followed by canals (31%), tanks (27%) and other sources (1%). The area cultivated under food crops is 4.22 million ha, with the major crops rice, sorghum, pearl millet, finger millet, blackgram and sugarcane. About 1.47 million ha are utilized for the cultivation of non-food and cash crops like cotton, peanut, coconut and others. Budhar & Palaniappan (1993; this volume) have provided a detailed example of land-use, crops and cropping systems in Dharmapuri district in north-western Tamil Nadu.

Table 1. Agro-climatic zones of Tamil Nadu. (PET= Potential evapo-transpiration).

Zone number	Name of the zone	Altitude (m)	Annual rainfall (mm)	Annual PET (mm)
I	North eastern	100-200	1105	1700
II	North western	200-600	875	1727
III	Western	200-600	718	1622
IV	Cauvery Delta	100-200	984	1932
V	Southern zone	100-600	857	1825
VI	High rainfall zone	100-2000	1420	1816
VII	Hilly zone	2000	2124	1213

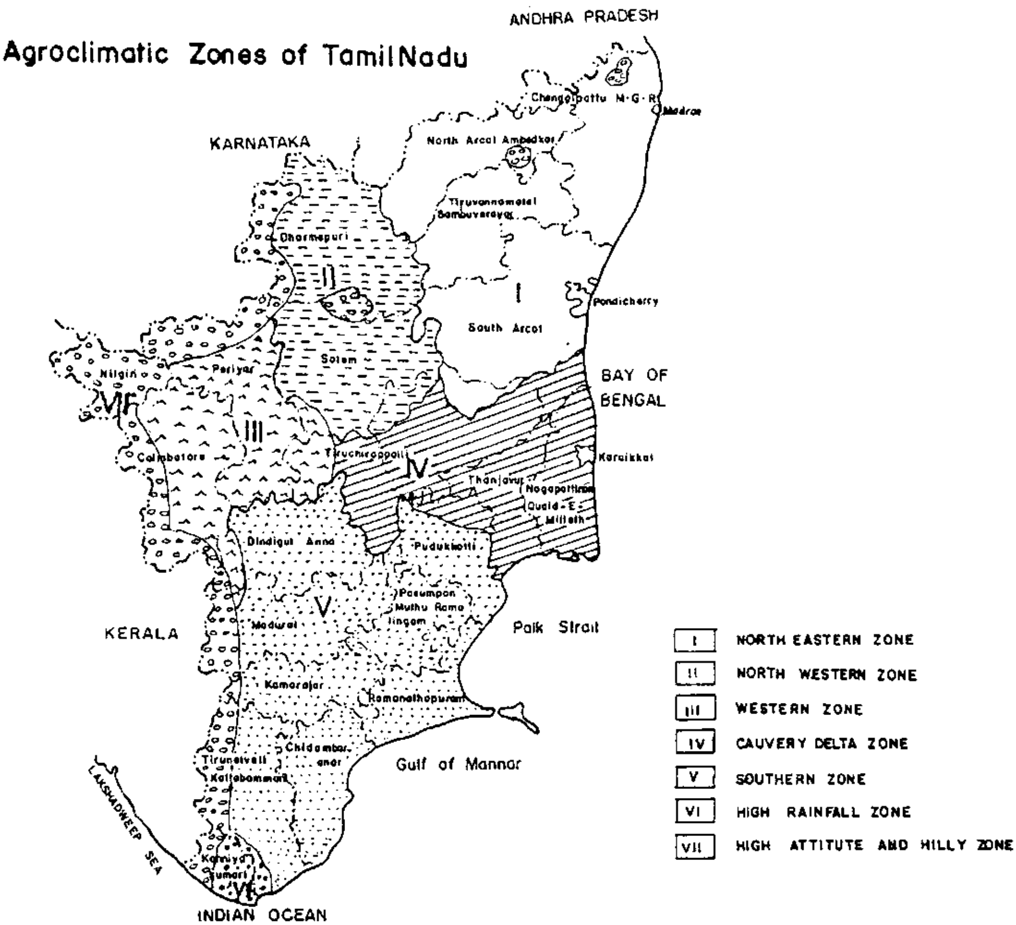

Figure 2. Agro-climatic zones of Tamil Nadu.

Table 2. Land utilization pattern in Tamil Nadu.

Land use	Area (m ha)	Percentage
Total geographical area	13.0	100
Forests	2.06	15.9
Barren and uncultivable lands	0.56	4.3
Land put to non-agricultural use	1.81	13.9
Permanent pastures and other grazing lands	0.15	1.1
Lands put under miscellaneous tree crops and grooves	0.18	1.4
Cultivable waste	0.30	2.3
Current fallow lands	1.42	10.9
Other fallow lands	0.83	6.4
Net are sown	5.69	43.8

Soils: classification and description

The soils of Tamil Nadu have been classified into six orders according to the USDA Soil Taxonomy (Soil Survey Staff, 1992): Entisols, Inceptisols, Alfisols, Ultisols, Mollisols and Vertisols (Table 3, Figure 3).

Entisols Soils of slight and recent development are included in this order. These soils do not have any diagnostic horizon other than that of an ochric epipedon. Subgroups identified under this order are listed in Table 3. Morphological and analytical data of Vannapatti series, a member of the Lithic Ustorthents are given in Figure 4 and Table 4. This soil group covers 37.5% of the total area of Entisols.

Inceptisols These soils are immature with a weakly developed (cambic) subsurface horizon. They possess an ochric epipedon. The subgroups identified under this order are listed in Table 3. A description of the Irugar series, a member of Typic Ustropepts, accounting for about 57.0% of the Inceptisols is given in Figure 4 and Table 4.

Alfisols These soils are matured with an illuviated (kandic/argillic) subsurface horizon. They have a high base saturation (more than 35%). The subgroups identified in the Alfisols are listed in Table 3. A description of the Palaviduthi series, a member of the Typic Rhodustalfs, constituting 40.4% of the total area under Alfisols is presented in Figure 4 and Table 4.

Ultisols These soils are well developed with an illuviated kandic/argillic horizon. They have a base saturation of less than 35%. Only one subgroup was identified, the Typic Haplohumults. A description of the Ooty series, a member of the Typic Haplohumults is given in Figure 4 and Table 4.

Mollisols These soils contain more than 1% organic matter in the surface (mollic) horizon. They have either a weakly developed cambic or strongly developed candic/argillic horizon. The subgroups identified are listed in Table 3. Mollisols occur in interior forest areas.

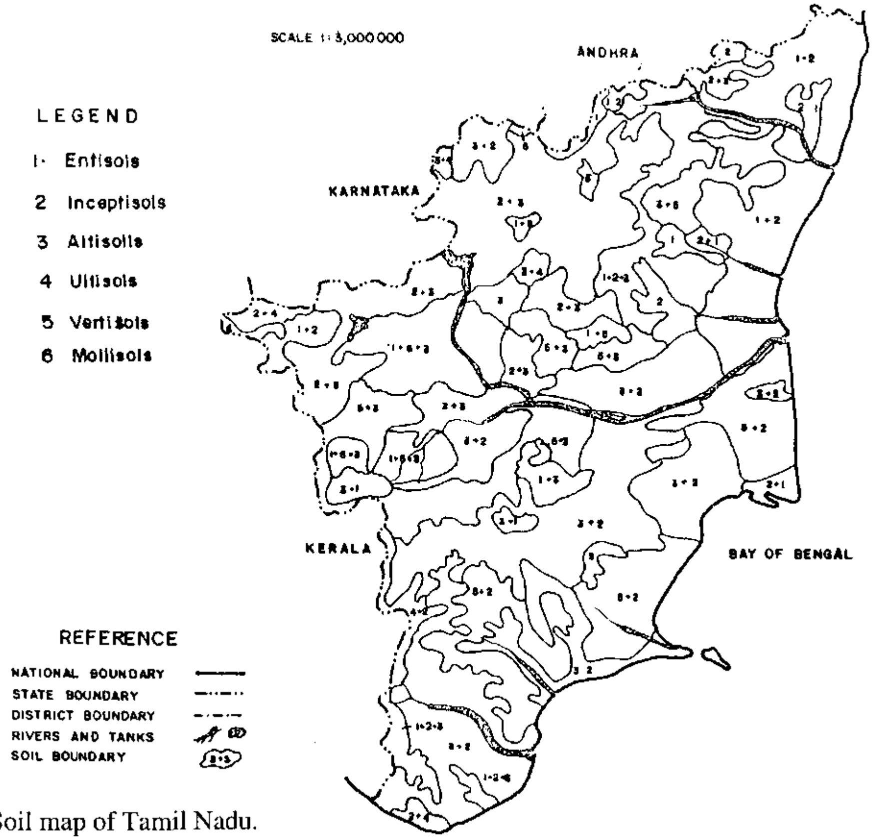

Figure 3. Soil map of Tamil Nadu.

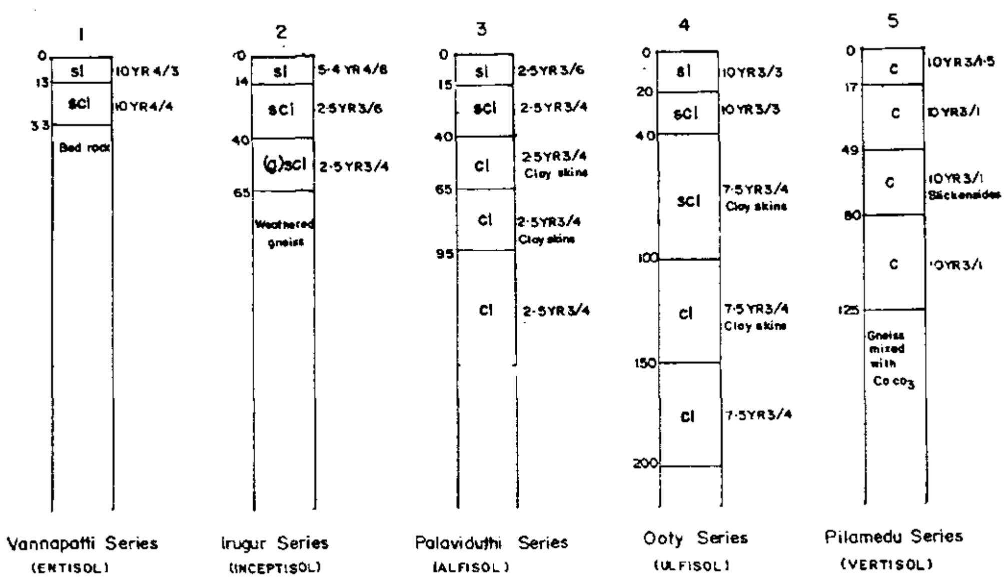

Figure 4. Profile diagrams of soils orders in Tamil Nadu.

Table 3. Areal extent of soil orders, sub-orders, great groups and sub-groups in Tamil Nadu (according to USDA Soil Taxonomy).

Order	Sub-order	Great group	Sub-group	Area (10^3 ha)	%
Entisols	Aquents	Tropaquents	Typic Tropaquents	16.6	
	Fluvents	Ustifluvents	Typic Ustifluvents	253.8	
	Orthents	Ustorthents	Lithic Ustorthents	26.6	
	Psamments	Ustipsamments	Aquic Ustipsamments	20.2	
			Typic Ustipsamments	178.7	
				792.9	6.1
Inceptisols	Aquepts	Halaquepts	Aeric Halaquepts	8.1	
			Typic Halaquepts	21.5	
		Tropaquepts	Aeric Tropaquepts	4.5	
			Typic Tropaquepts	28.2	
	Tropepts	Dystropepts	Lithic Dystropepts	0.2	
			Typic Dystropepts	38.9	
		Eutropepts	Typic Eutropepts	38.2	
		Humitropepts	Oxic Humitropepts	68.3	
			Typic Humitropepts	143.5	
		Ustropepts	Lithic Ustropepts	337.8	
			Vertic Ustropepts	1444.3	
			Oxic Ustropepts	267.1	
			Fluventic Ustropepts	406.2	
			Typic Ustropepts	3728.1	
				6534.9	50.3
Alfisols	Udalfs	Paleudalfs	Rhodic Paleudalfs	20.7	
			Mollic Paleudalfs	24.6	
	Ustalfs	Paleustalfs	Psammentic Paleust.	30.9	
			Kandic Paleustalfs	260.4	
			Rhodic Paleustalfs	632.2	
			Typic Paleustalfs	47.2	
		Rhodustalfs	Lithic Rhodustalfs	30.3	
			Kandic Rhodustalfs	185.8	
			Typic Rhodustalfs	1583.2	
		Haplustalfs	Lithic Haplustalfs	9.3	
			Aquic Haplustalfs	78.2	
			Kanhaplic Haplustalfs	158.7	
			Typic Haplustalfs	855.1	
				3916.6	30.3
Ultisols	Humults	Haplohumults	Typic Haplohumults	126.9	1.0
Mollisols	Udolls	Argiudolls	Typic Argiudolls	27.6	
		Hapludolls	Typic Hapludolls	7.6	
	Ustolls	Argiustolls	Typic Argiustolls	6.4	
				41.6	0.3
Vertisols	Usterts	Chromusterts	Udorthentic Chromusterts	163.6	
			Udic Chromusterts	35.2	
			Entic Chromusterts	190.5	
			Typic Chromusterts	352.5	
		Pellusterts	Udic Pellusterts	40.5	
			Entic Pellusterts	41.8	
			Typic Pellusterts	86.6	
				910.7	7.0

Table 4. Physico-chemical properties of soil orders of Tamil Nadu.

Soil property	Entisol	Inceptisol	Alfisol	Ultisol	Vertisol
Clay (%)	15.2	20.0	28.5	22.6	40.2
Silt (%)	6.1	7.2	5.6	7.3	9.0
Fine sand (%)	25.6	20.6	18.1	25.5	28.5
Course sand (%)	50.7	48.8	45.2	40.2	30.2
Organic carbon (%)	0.3	0.1	0.3	0.4	0.2
pH	7.6	7.2	7.8	5.6	8.0
EC dsm^{-1}	0.2	0.4	0.2	0.2	0.8
$CaCO_3$ (%)	-	-	0.6	-	2.6
CEC (me 100 g^{-1})	16.9	20.5	-	12.0	38.9
Base saturation (%)	65.6	85.9	80.5	30.2	94.0

Vertisols These are dark grey, clayey, swelling and shrinking soils which develop deep cracks during summer. Vertisols are classified into subgroups as listed in Table 3. A description of the Pilamedu series, a member of the Typic Chromusterts, accounting for 38.7% of the Vertisols area is presented in Figure 4 and Table 4.

Table 5. Areal extent of land suitability classes in Tamil Nadu.

Land suitability class/subclass	Area (m ha)	Percentage
Good cultivable lands		
(a) with erosion problem	0.313	2.41
(b) with drainage problem	0.254	1.95
(c) with soil problems	0.488	3.75
Moderately good cultivable lands		
(a) with erosion problem	0.719	5.53
(b) with drainage problem	0.200	1.54
(c) with soil problems	6.050	46.54
Fairly good lands suitable for limited cultivation		
(a) with erosion problem	0.475	3.65
(b) with soil problems	1.595	12.27
Lands well suited for forestry		
(a) with erosion problem	0.858	6.60
(b) with soil problems	0.259	1.99
Lands fairly well suited for forestry		
(a) with erosion problem	0.559	4.30
(b) with soil problems	0.118	0.91
Lands suitable for recreation	1.112	8.56

Land suitability and soil constraints

Land suitability classes

The land area of Tamil Nadu has been mapped and classified according to its suitability to (overall) arable cultivation and forestry. The classifications are based on land and soil conditions. The areal extent of the various suitability classes in Tamil Nadu is given in Table 5. Also, the land area of Tamil Nadu has been classified according to its suitability for irrigation. This classification was based on soil and land conditions and on the behaviour of soils under the altered water regime brought about by the introduction of irrigation. The areal extent of the irrigability classes in Tamil Nadu is given in Table 6.

Moisture retention capacity of soils

Based on the fluctuation of the ground water table, Tamil Nadu soils are categorized into two groups, viz., soils with a shallow water table and soils with a deep water table. Most of the soils fall under the second category of having a deep water table.

The moisture content of Tamil Nadu soils was studied at different moisture tensions (0.1 - 10.0 bar). In general, the moisture contents were highest in Vertisols, followed by Alfisols and Entisols. The moisture content was highest in all the soils at 0.1 bar and then decreased as the moisture tension increased. The decrease of moisture content with the increase in moisture tension is gradual in Vertisols but rather drastic in Alfisols and Entisols (Figure 5).

Table 6. Areal extent of land irrigability classes in Tamil Nadu.

Land irrigability class/subclass	Area (m ha)	Percentage
Lands with moderate limitations		
(a) with topographic limitations	0.286	2.20
(b) with drainage problem	0.260	2.00
(c) with soil problems	1.755	13.50
Lands with severe limitations		
(a) with topographic limitations	0.593	4.56
(b) with drainage problem	0.130	1.00
(c) with soil problems	4.615	35.50
Lands with very severe limitations		
(a) with topographic limitations	0.390	3.00
(b) with drainage problem	0.007	0.05
(c) with soil problems	1.950	15.00
Lands temporarily classified as unsuitable for irrigation	0.767	5.90
Lands permanently classified as unsuitable for irrigation	2.247	17.29

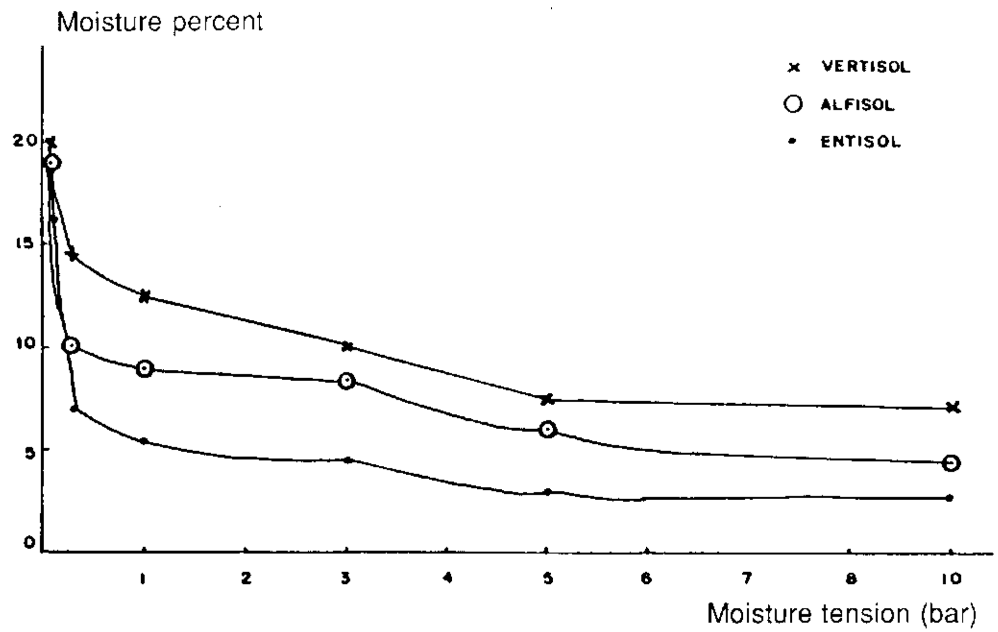

Figure 5. Moisture retention curves of some soils of Tamil Nadu.

Presence of impermeable layers and hard pans

Investigations are under progress to delineate the physical constraints of the soils in Tamil Nadu. Only 25% of the total land area has been studied so far. In the studied area, 0.12 m ha are affected by a subsoil hard pan. This hard pan occurs predominantly in Alfisols (Rhodustalfs and Haplustalfs). The hard pan is characterized by high bulk density (1.7 - 1.8 g cm^{-3}) and concentration of iron and aluminium oxides. The hard pan adversely affects root penetration, air and water movement and ultimately, crop yields. Loosening the subsoil by chisel plough (at 40 cm depth, at 0.5 m interval) and applying farm-yard manure or pressmud at 10 t ha^{-1} was found to be an economically feasible technology to alleviate the problems caused by hard pans. Chiselling reduced the bulk density, improved the hydraulic conductivity and root growth of crops and resulted in higher yields by 20 - 30%. The technology was found to be beneficial to crops like sorghum, tapioca, groundnut, maize, blackgram, tomato and chillies under rainfed and irrigated conditions (Natesan et al., 1991).

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Crops and cropping systems in Dharmapuri district in the north-western agro-climatic zone of Tamil Nadu, India

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Abstract

Current crops, cropping patterns and crop production constraints in Dharmapuri district, Tamil Nadu, India, are described and analysed. About 75% of the net sown arable land area (which accounts for 33% of the total districts area) is under rainfed cultivation. The main crops are sorghum, millet, groundnut, pulses and grams. Cropping systems have been 'shaped' by many factors: amount, distribution and timing of rainfall, domestic food, fodder and fuel requirements, and socio-economic obligations. The most important single crop in the irrigated environments is rice. The major production constraints lie in the delayed transplanting of rice-seedlings because of late availability of irrigation water, either from canals, reservoirs or wells. Consequently, the rice-seedlings are beyond the optimum age for transplanting, and the delayed crop suffers cold-injury during flowering. Other irrigated crops are cotton and sugarcane.

Introduction

In India, increasing the production per unit area has become a necessity due to the limitation of cultivable land and to increasing demographic pressure. Today, more than 40% of the geographical area of India has already been put under plough and further availability of agricultural land is negligible. The estimated food requirement to feed one billion Indians in 2000 A.D. is about 225 million tonnes. This means that, with respect to the present situation, an additional amount of food of 75 million tonnes has to be produced with the currently available land. Thus, it is important to know the levels of potential crop yields that can be obtained in various agro-climatic environments. Potential crop yield levels can be derived from field experiments and from crop growth modelling. Thiyagarajan et al. (1993; this volume) and Ramaswami & Selvaraju (1993; this volume) have shown the use of crop growth and water balance models for estimating rice yield potentials in the state of Tamil Nadu (India). By comparison with actual cropping systems and with natural environmental conditions (soil, weather), yield gaps can be analyzed and agricultural research can be directed to areas which show a promising scope for increasing crop productivities. For Tamil Nadu State, the general agro-ecology and natural environment (geology, climate, soils) were inventorized and described by Palaniappan et al. (1993; this volume). The next step would be to have an in-depth description of the current forms of land use in the state, which is the scope of this paper. Cropping systems, crops and production constraints in Dharmapuri district in the north-west of Tamil Nadu State are described in detail, along with the overall agro-ecology and natural environment. From the analyses of crop production constraints, some suggestions to increase crop productivity are given at the end of the paper.

Dharmapuri district, Tamil Nadu , India

Dharmapuri district, in the north-western zone of Tamil Nadu lies between 11° 45' and 13° 01' north latitude and 77° 13' and 78° 45' east longitude with an altitude of 400 meters above mean sea level. The district is the 9th largest in the State with an area of 9633 km^2, constituting 7.4% of the State's total area. The district borders the States of Andhra Pradesh and Karnataka on its northern and western side, and the districts North Arcot, South Arcot and Salem by the south. Administratively, the district is divided into eight so-called 'taluks' (Figure 1) viz., Dharmapuri, Palacode, Pennagaram, Harur, Uthangarai, Hosur, Krishnagiri and Denkanikotta. The population of Dharmapuri district is 1.93 million, living in about 5000 villages.

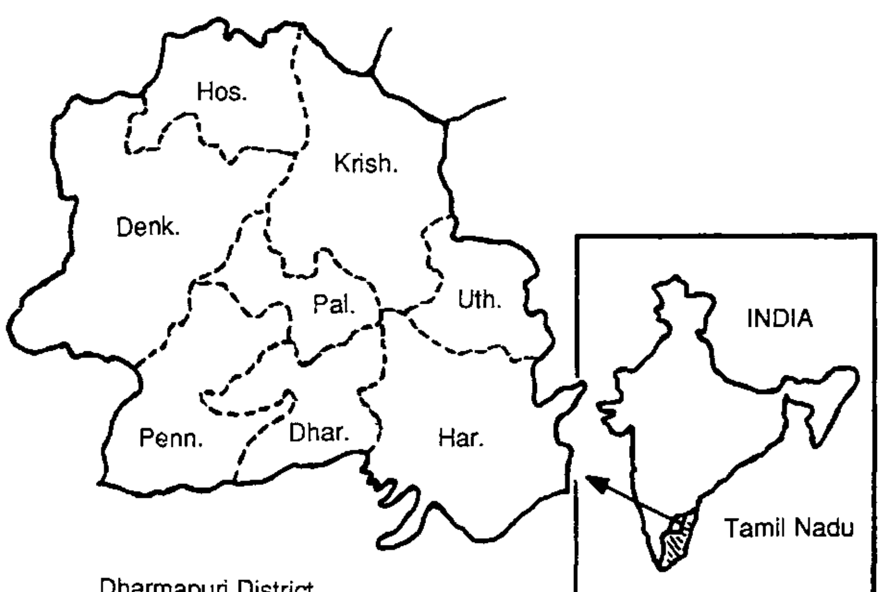

Figure 1. Location map of Dharmapuri district in Tamil Nadu State, India. The dotted lines indicate the boundaries between the eight taluks: Hos. = Hosur, Denk. = Denkanikotta, Krish. = Krishnagiri, Pal. = Palacode, Penn. = Pennagaram, Dhar. = Dharmapuri, Har. = Harur, Uth. = Uthangarai.

Climate

Rainfall The average monthly amount of rainfall and the average number of rainy days (defined as having 2.5 mm or more rainfall in a day) in Dharmapuri district are given in Table 1. Dharmapuri district enjoys both the southwest (June to September) and northeast monsoon (October to December) rains. The summer months are March-April, and the winter months are January - February. The average annual rainfall of the whole district is 869 mm received in 50 rainy days. Most rainfall is received during the southwest monsoon, 384 mm, and during the northeast monsoon, 317 mm, accounting for 44 and 34% of total annual rainfall respectively. Only in Harur taluk, the rainfall is more in the northeast monsoon season than in the southwest monsoon season. In all the taluks, the rainfall is highest in October followed by September, May, August and November. Comparatively, the rainfall is low from December to April.

Temperature The mean *monthly* maximum and minimum temperatures of Dharmapuri district are also given in Table 1. The *daily* maximum temperature ranges from 23 - 42 °C and the minimum temperature from 12 - 31 °C. Being an interior region, the diurnal range of temperature is large, particularly in the dry and hot (summer) seasons. The minimum temperature at Hosur, Denkanikotta and Krishnagiri invariably goes below 14 °C. In the high elevation taluks (660 - 960 m) of Hosur and Denkanikotta, minimum temperatures of 10 - 18 °C prevail for a long period from October onwards. These conditions favour the cultivation of temperate vegetable crops in these areas.

Table 1. Mean monthly maximum (T_{max}) and minimum (T_{min}) temperature (°C), and mean monthly rainfall (R_r, mm) and number of rainy days (R_d, $\geq$ 2.5 mm rain in a day) at Dharmapuri district, Tamil Nadu, India. Mean values were calculated from weather stations at the 8 taluks with long-term observations varying from 1940 - 1983 and 1963 - 1989.

Months	T_{max}	T_{min}	R_r	R_d
January	29.6	18.0	6.5	0.51
February	30.0	19.6	7.1	0.45
March	35.3	20.3	11.5	0.66
April	38.5	23.6	34.4	2.48
May	38.8	24.5	109.6	6.37
June	34.8	24.6	52.4	3.63
July	33.8	24.3	77.8	5.35
August	33.3	22.3	97.5	5.92
September	33.1	22.8	156.0	7.49
October	32.3	21.8	180.2	9.27
November	30.4	19.6	94.9	5.49
December	29.9	18.0	41.5	2.43

Soils

The soils of Dharmapuri district are of residual type developed on weathering bedrock. The soils in the district are grouped into different series, of which the characteristic features are given below (see also Palaniappan et al., 1993 (this volume), for soil descriptions of whole Tamil Nadu):

Hosur series A brown non-calcareous soil, with colours ranging from dark brown to reddish brown, deep to very deep (relatively), mostly loamy sand to sandy clay loam texture and well drained. The soil reaction ranges from medium acid to neutral and the pH increases with increasing depth of the profile. Soils were mainly developed from granitic gneiss with quartz veins. The slopes range from 1 to 5%.

Krishnagiri series A dark greyish brown, very deep calcareous soil. The texture of the surface soil ranges from sandy loam to sandy clay loam while that of the subsoil ranges from clay loam to clay. The pH of the surface soil ranges from neutral to alkaline. The soils were mainly developed from weathered calcareous gneiss, though in Krishnagiri taluk, black granite and pyrite have been reported. In the Krishnagiri Reservoir Project area, out of 4000 ha, nearly 2500 ha of land suffers from drainage and alkalinity problems.

Vannapatti series These soils are yellowish red to red in colour, well drained, non-calcareous, moderately deep to deep, loamy sand to sandy clay loam texture, and neutral in reaction. The soils were mainly developed from weathered gneiss and occur mostly in sloping and to a smaller extent in undulating rolling landscapes.

Dharmapuri series. A black calcareous soil, very deep, heavy textured, moderately well drained with moderate to slow permeability. The pH ranges from 6.4 to 8.8. The texture ranges from sandy loam to clay.

Harur series. This series is present in the Harur and Uthangarai taluks in a limited area only. The soils are yellowish brown to dark grey, calcareous, deep to very deep, medium to heavy textured, neutral to alkaline in reaction, moderately well drained having moderate to slow permeability.

Land use and cropping patterns

The net sown area in Dharmapuri district occupies 33% of the total land area, and the forests cover about 34% (Table 2). The net sown area is high in Harur taluk (23.5% of total sown area in Dharmapuri district) and in Krishnagiri taluk (15.3%); it is lowest in Pennagaram taluk (7.2%). The forested areas are largest in Harur, Denkanikotta and Krishnagiri taluks, constituting about 20.3, 19.5 and 18.3% respectively of the total forest cover in Dharmapuri. The forested area is lowest in Pennagaram taluk (only 2.8% of total). The area under barren and uncultivable waste and permanent pastures is high in Hosur taluk. The land area under miscellaneous trees and under current fallow is high in Krishnagiri taluk and the cultivable waste area is high in Denkanikotta taluk.

The existing cropping patterns have been shaped by many factors such as rainfall

Table 2. Land use (in hectares) in the eight taluks of Dharmapuri district (1980 - 1981).

Area	Dharm.	Uthang.	Palacode	Penn.	Harur	Krishn.	Hosur	Denkan.	Total
Geographical area	85993	138402	96181	61610	84665	172001	152543	151926	963321
Forests	26037	59773	23526	9170	28117	66402	50364	63790	321184
Barren and uncultivated waste	3368	5894	7104	4981	1993	11599	27484	5947	68370
Land put under non agricultural use	6057	8315	5651	5799	4947	8592	5306	5386	50053
Cultivable waste	1881	174	998	2533	1570	2388	2337	4640	16521
Permanent pastures	1310	905	894	1555	908	1178	3534	3251	13535
Land under miscellaneous trees	124	3898	501	810	174	601	1208	1427	8743
Current fallows	14757	28460	20448	12068	8568	5355	25614	27555	142825
Other fallows	1314	2368	1916	1786	989	849	4031	3911	17164
Net sown	31062	48610	35138	22945	37396	74709	32661	36015	318536
Total cropped area	35427	71123	42508	27746	41367	83785	33568	42880	378404

(amount, distribution, onset monsoons), availability of irrigation water, domestic requirements by the farmer, fodder and feed need of the livestock and socio-economic obligations. The cropping systems are highly flexible to suit the timely need of the farmer. Throughout time, farmers have developed their own contingent crop plans to suit the aberrant weather conditions. In general, the existing cropping systems can be grouped into two broad categories: dryland and wet (submerged) / garden (irrigated) land:

Dryland

1. Groundnut + Redgram + Castor (Jul - Oct) - Horse gram (Nov - Jan)
2. Little millet - Horsegram / Coriander (Oct - Dec)
3. Finger millet + Lablab + Sorghum + Castor (Aug - Nov)
4. Sesamum (May - Aug) - Horsegram (Sep - Dec)
5. Sorghum + Lablab + Cowpea + Castor (Jul - Dec)
6. Kodo millet (Jul - Nov)
7. Sesamum (Apr - Jun) - Finger millet / Tomato (Aug - Dec)

In Dharmapuri district, the majority of the cultivated land area is under rainfed farming (77% of net sown area). In Hosur and Denkanikotta taluks, finger millet is the main crop with intercrops such as sorghum (great millet *Sorghum vulgare*), lablab (*Dolichos lablab*), niger (*Guizotia abyssinica*) and mustard (*Brassica juncea*). Sesamum (*Sesamum indicum*) is raised making use of the summer showers and is followed by horsegram (*Dolichos viflorus*). In Krishnagiri, Palacode, Dharmapuri, and Pennagaram taluks, sorghum (Co19, a long duration open panicle type) is raised with intercrops like redgram (*Cajanus cajan*) and lablab. Groundnut and little millet are also grown taking the advantage of southwest monsoon rains and are usually followed by horsegram in the northeast monsoon season. In Harur and Uthangarai taluks, where the rainfall is comparatively low, the majority of the cultivated area is under millets such as sorghum, little millet or long duration kodo millet (*Paspalum scrobiculatum*). However, if the rainfall is favourable, the cash crop of groundnut is preferred by the farmers. In all the major crops, inter-and mixed-cropping is practised to safeguard against failure of the major crop in unfavourable seasons.

Wet/Garden land

1. Rice (Jul-Nov) - Rice (Dec - Mar)
2. Rice (Jul-Nov) - Groundnut (Dec - Feb) - Pearl millet (Mar - May)
3. Rice (Jul-Nov) - Finger millet (Dec - Feb)
4. Rice (Jul-Nov) - Tomato (Dec - Apr)
5. Rice (Jul-Nov) - Rice (Dec-Mar) - Finger millet / Pearl millet (Apr - Jun)
6. Cotton (Aug-Feb) - Finger millet / Great millet / Pearl millet (Mar - May)
7. Tomato (Jul-Oct) - Potato / Cabbage (Nov - Mar) - Finger millet (Apr - Jun)
8. Sugarcane - Sugarcane ratoon - Rice

Of the total net sown area in Dharmapuri, some 23% is under irrigation (i.e. 73,296 ha). The main source of irrigation is by wells accounting to 69.6% of the irrigated area. The other sources of irrigation are tanks and canals (Table 3). In Dharmapuri, there are eight major reservoir projects which supply water to about 19,236 ha. Among the taluks, the net irrigated area is largest in Krishnagiri (27.7% of total irrigated area in Dharmapuri) and in

Table 3. Sources of irrigation in different taluks of Dharmapuri district, Tamil Nadu.

Irrigation sources	Dhar.	Krish.	Pal.	Penn.	Uth.	Harur	Hosur	Denk.	Total
Canals	970	5166	796	-	1232	929	28	319	9440
Tanks	1411	2238	1087	1319	240	1987	826	2532	11640
Wells	5741	12907	4578	2860	5450	14814	1432	3255	51037
Other sources (rivers, dams)	-	-	-	-	238	-	941	-	1179
Total area irrigated	8122	20311	6461	4179	7160	18671	2286	6106	73296

Harur (25.5%). The area under irrigation is smallest in Hosur and Pennagaram taluks.

Rice (*Oryza sativa*) based cropping systems are practised in almost all (farm-)holdings which are fed by wells, tanks or canals. In most parts of the reservoir project areas, rice is the first crop. In canal fed tracts like Krishnagiri Reservoir Project Command Area, a first rice crop (Jul-Nov) is followed by a second rice crop (Dec-Mar) depending on the availability of canal water. In addition, where water is lifted from wells, a third crop like groundnut (*Arachis hypogaea*), pearl millet (*Pennisetum typhoideum*), finger millet (*Eleusine coracana*) or vegetables is raised. In areas solely fed by wells, the possibilities for a second crop after rice depend on the water level in the wells: during July-November either rice or cotton or finger millet is raised which is followed by groundnut, finger millet, tomato (*Lycopersicum esculantum*) or cabbage (*Brassica oleracea* L *capitata*) during December to February.

Cotton (*Gossypium* sp) based cropping systems are more common in garden lands fed by wells. After the harvest of winter cotton (Aug-Feb), pearl millet or tomato is grown in the summer months. Summer cotton (Feb - Jul) is grown after the harvest of rice in some places.

Sugarcane (*Saccharum officinarum*), turmeric (*Curcuma longa*) and flower crops like crosandra and chrysanthemum (*Chrysanthemum* sp) form the cash crops in irrigated areas, especially in Hosur and Denkanikotta taluks. Cultivation of grapevine in garden land is unique in Krishnagiri, Hosur and Uthangarai taluks. The vines are maintained for 10 - 12 years with two harvests in a year.

Single crops

Rice

The major rice areas are found in the taluks of Krishnagiri, Dharmapuri and Palacode. The largest area is in Krishnagiri taluk where the crop is raised by canal water from the Krishnagiri Reservoir Project. In other taluks, the crop is raised both by canal and well water. The optimum season for rice is from July to November (first crop season). The time of transplanting is invariably dependent on the time of release of water in the irrigation projects (reservoir and canal water). In years with early release, two rice crops are raised viz., July - November and December - March (second crop season). Similarly, the time of transplanting of rice on well-irrigation depends on the water level in the wells, which is highly variable due to erratic distribution of rainfall.

In the first rice season, medium duration varieties like Bhavani, Paiyur-1, GEB24, IR20, Co43 and Co44 are raised. In the second season short duration varieties like ADT36, TKM9 and IR50 are preferred because of limited water availability (in reservoirs as well as in wells). The major production constraint in rice cultivation is the non-optimum age of the rice-seedling at delayed transplanting. Anticipating the rainfall/release of water from the reservoir, nurseries are raised well in advance of the optimum season. The farmers often are not in a position to take up the transplanting at the optimum age of the seedling. They transplant 'aged' seedlings which is one of the major causes for reduced yields. In some years, transplanting of the first rice crop is even delayed till the end of September. The late transplanted crop is usually subjected to low temperature stress at flowering in December. Similarly, crops that are transplanted in November suffer from cold stress and exhibit stunted growth. Yellowing due to micronutrient deficiencies also contributes to reduced yields. Due to continuous canal irrigation and subsequent (local) raise of the ground water table, salt problems also occur. Salt problems becomes more acute during the second crop season in areas of poor surface drainage. So in the salt-problem areas, salt tolerant varieties like Co43 are recommended along with reclamatory tmeasures such as the application of gypsum and the provision of drainage to leach the salts.

Cotton

On the whole, cotton does not occupy a larger area, but but there is a sizable cotton area in Harur and Uthangarai taluks. Cotton is raised in two seasons, winter (Aug - Feb) and summer (Feb - Jun). The crop is grown solely under irrigation from wells. The commercial varieties like MCU5, MCU9, LRA5166 and hybrids such as DCH32 and Varalakshmi are cultivated. The cultivation of cotton is gaining popularity because of the better adaptation of this crop to the prevailing climatic conditions. The crop is usually grown in rotation before or after a rice crop.

Sugarcane

The major area under this crop is found in the taluks of Harur and Palacode. These taluks are especially noted for the high yield potential and high percentage of sugar recovery. The area under this crop is increasing because of the establishment of a co-operative sugar factory at Palacode. Farmers are given financial incentives based on the overall sugar recovery of this factory. The ruling variety is CO6304. However, other varieties such as COC771, COC772, COC6896 and Co419 are also cultivated. Some farmers prepare jaggary by raising special varieties, Co853, Co62174, COC671,Co62175 and Co740. Mostly, sugarcane is grown in one ratoon and sometimes in two ratoons. Sugarcane is usually rotated with rice, summer cotton or irrigated groundnut. Since this crop is solely raised under irrigated conditions, moisture stress in usually experienced in the summer months (Mar-May) when water availability becomes scarce. Suitable planting methods like paired row techniques and alternate furrow irrigation are advocated to minimise the water requirements. The presence of a semiparasitic weed *Striga lutea* is posing problems to the cultivators. Weed control methods that involve the application of herbicides and the adoption of proper crop rotation with cotton or chillies are recommended for eradication of this problematic weed.

Sorghum

Nearly 75% of the sorghum area is under rainfed condition. Rainfed sorghum is raised as a single crop from June - July to December - January. About 26% of the sorghum area is found in Harur taluk followed by Dharmapuri taluk (23%). The crop is grown to a lesser extent in the taluks of Krishnagiri, Uthangarai and Palacode.

The traditional long duration (150 - 160 days) photosensitive variety Co19 is raised with intercrops like lablab. This variety is noted for its drought-tolerance during the vegetative phase and for its high rejunuvative capacity at later stages when sufficient soil moisture is available. The grain is white in colour, borne in loose panicles which are usually not damaged by rain, attack of earhead bug and birds. The average grain yield is 400 - 500 kg ha^{-1}. The fodder quality of the straw is moderate and only two-thirds of the upper parts of the crop is used for fodder. The remaining stalks and straw are used for fuel purpose. The seed is broadcast and covered with a shallow layer of soil with light implements. Usually, no fertilizers are applied and no plant protection measures are taken. Agricultural research revealed the possibility of having a two-crop system. A pulse crop like greengram (*Phaseolus mungo*) or cowpea (*Vigna sinesis*) can profitably be raised from June-September and thereafter, short duration sorghum varieties like Co25 or Co26 can be raised with intercrops. Budhar et al. (1987) found that greengram (Jun - Sept) followed by sorghum (Oct - Dec) with intercropped cowpea gave a yield of 1029 and 686 kg ha^{-1} of gram and grain respectively with a field duration of 177 days. Also, it was found that fertilizer application increased sorghum grain yield considerably. A fertilizer application of 40:20:0 kg NPK ha^{-1} is recommended. Split application of nitrogen at the time of sowing and 30 days after sowing is more remunerative along with the applicaion of biofertilizers like *Azospiri llum.*

Sorghum is grown under irrigated condition in only a limited area of garden land, usually after the harvest of rice. The varieties suggested are Co24 and Co25.

Finger millet

Finger millet forms the staple food for the Dharmapuri district's farming community. Among the taluks, large areas are found in Denkanikotta taluk followed by Hosur and Krishnagiri taluks. The crop is raised solely under rainfed condition in Denkanikotta and Hosur taluks from July to November. The traditional long duration (150 - 160 days) cultivars Nallagaddaragulu, Posurugaddaragulu and Sannagaddaregulu are used. These long duration varieties are drought tolerant during the early stages with remarkable tillering at optimum soil moisture levels. These varieties have open panicles with lengthy fingers. The seed is broadcast using a heavy seed rate and is covered with earth. Many intercrops like lablab, redgram, sorghum, cowpea, niger and mustard are grown mainly to mitigate the risk of failure of the main crop and to meet domestic requirements. The farmers do not apply any fertilizer. The traditional varieties currently used have low yield levels and extension services recommend high yielding varieties such as Paiyur-1, Indaf-5 and Indaf-8. The results of the experiments carried out at the Regional Research Station, Paiyur, clearly showed the benefits of fertilization with the improved varieties. It was also found that, by using biofertilizers such as Azospirillum, 50% of the nitrogen requirement can be saved (Gopalaswamy & Narayanan, 1985). Incidence of blast disease is another major constraint in increasing the productivity.

The area of finger millet under irrigation crop is considerably less than that of the rainfed crop. The major season for the irrigated crop is December - February. The crop is usually preceded by the first crop of rice.

Little millet

This crop is grown in an area of 57,600 ha solely under rainfed condition. The crop is usually sown in marginal and submarginal lands and also at the foot of hills. Little millet can grow under low levels of management and with low soil fertility. The crop is highly drought tolerant and is sown at the onset of early rains in land that is not suitable for other dryland crops such as groundnut or finger millet. In other lands, that are in principle suitable for groundnut, sorghum and finger millet, little millet is sown when the monsoon is delayed beyond the optimum sowing dates for these other crops (little millet is preferred above late sowing of e.g. groundnut or sorghum). The major area of little millet is found in Harur and Uthangarai taluks. The seed is broadcast, and no thinning, weeding or intercultivation takes place.

Horsegram

Horsegram is a winter season crop only, and is grown after the harvest of groundnut or little millet. In the whole of Tamil Nadu state, the major area for horsegram is found in Dharmapuri district, especially in the Harur, Hosur and Uthangarai taluks. The crop is usually sown in the middle of October to the end of November. The seeds are broadcast and covered with earth. The crop is capable of growing on residual available moisture and atmospheric dew. The grain as well as haulms are used. Good varieties and appropiate production technologies are the constraints for horsegram. Crop substitution studies carried out the Regional Research Station, Paiyur, revealed that cowpea was more remunerative and could substitute horsegram under early sowing conditions. Under normal and late sown condition, horsegram was found to be the better crop. The optimum spacing is 30 x 10 cm. The application of phosphorus along with seed inoculation of rhizobial culture increased the grain yield of horsegram (Gopalaswamy & Narayanan, 1985).

Groundnut

The area under (dryland) groundnut fluctuates year by year, depending on the onset of the southwest monsoon. In general, groundnut is grown in some 19000 ha in Krishnagiri taluk, and in some 9000 ha in Uthangarai taluk. Mostly, bunch varieties are grown. In Hosur taluk, a spreading type, long duration, local cultivar namely 'Perunadan' is cultivated. Since groundnut is a high input-demanding crop, it is raised in (at least) moderately fertile soils with heavy doses of farmyard manure. Usually, no basal dressing is given. Improved varieties like Co1, Co2, TMV7, JL24 and TMV12 are recommended. Maintenance of optimum population is the greatest constraint in groundnut production, mainly because the seeds are dibbled behind the country plough at various depths. Improper care in the selection of seeds and non-treatment of seeds with fungicides results in heavy mortality of seedlings. To overcome this, seed drills are to be used. Furthermore, seed treatment with fungicides and the use of enriched farmyard manure with phosphorus and potassium is recommended. Application of gypsum on the 40 - 45th day after sowing is advocated to increase the grain filling of the kernels. This practice is becoming popular among the farmers.

The area under irrigated groundnut is relatively small. The major season for the irrigated groundnut is December - March after rice.

Dry mango

Mango (*Mangifera indica*) is grown under rainfed conditions in Krishnagiri and Palacode taluks. Varieties such as Bangalora (40%), Neelam (40%), Rumani and Sendura (10%) are mainly being used. The dry weather prevailing from January to May is quite congenial for flourishment of mango trees. Mango saplings are planted with the onset of the southwest monsoon in pits. During the first two years, 'pot-watering' is practised during the summer months. Thereafter, irrigation is stopped and the trees have to make do with natural rainfall. Intercropping with pulses or with little millet is practised until the 5th year when the trees start bearing fruit.

Cold vegetable

The cultivation of cold vegetables like cabbage, cauliflower (*Brassica oleracea* L *totrytis*), beans (*Phaseolus vulgaris*), knolkhol (*Brassica caulorapa*) and potato (*Solanum tuberosum*) are popular in Hosur and Denkanikotta taluks in the winter months. The weather factors such as temperature and humidity are quite conducive for growing this kind of ('hilly') vegetables.

Suggestions and incentives to increase crop productivion

The major arable area in Dharmapuri district is under rainfed crops. Research findings revealed that it is possible to increase crop production in drylands by applying fertilizers. Farmers, however, are reluctant to invest money in fertilizers because of the apparent risk associated with the erratic distribution of the rainfall. Few of the farmers who ventured to apply the recommended fertilizer schedules reaped good harvest.

Soil and moisture conservation methods may be extended to larger areas. In Hosur and Denkanikotta taluks, rice cultivation starts only in September when reservoirs behind check dams are filled with rain water so that the crop is invariably subjected to low temperature stress at flowering which results in decreased yields. Similar situations are also frequently met with in canal and well-fed areas. The provision of cold tolerant varieties with a package of appropriate agro-techniques may lead to increased production.

The area under sodic (saline) soils is increasing. Though the reclamatory measures advocated by the extension functionaries are highly paying, the farmers are not in a position to invest the required money. In saline areas, credit facilities may be made available to farmers.

It has been demonstrated that mixed farming with sericulture, e.g. 'milk-animals' or poultry, is more remunerative than arable farming alone. Farmers should be encouraged by giving liberal financial assistance for the purchanse of milk animals etc., In some areas of Dharmapuri district, tomato is cultivated during the summer months on a commercial scale. A glut is usually observed at the time of peak harvest. The provision of cold storage facilites will ease the glut. Also, inducing industries to convert into bye products (value added products) like paste, juice and pickles would pay a remunerative return to the farmers.

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Agro-climatic zoning: a water balance approach for rainfed rice in Tamil Nadu, India

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Abstract

To identify the potential for rainfed rice production in the north-east monsoon season (October-December) in Tamil Nadu, India, yield index values derived from water balance book-keeping were used for a qualitative suitability assessment. Meteorological data were collected from 115 taluk (subdistrict) level stations and grouped into 16 zones. Soil data were taken from soil maps. Next to climatic parameters, the water holding capacity of the soil was found to be a major factor in determining the suitability for rainfed rice production. Except for a few coastal areas in the north and south, characterized by river alluvium, coastal alluvium, red loamy and deep red soils, all parts of Tamil Nadu were classified as 'not suitable'. The mentioned soils in the coastal areas had a relatively high water content at the start of the growing season and were classified as 'suitable'. The red sandy soils in the same coastal areas were classified as 'not suitable' because of their low water holding capacity. The interior zones of Tamil Nadu experienced water deficit throughout the growing season.

Introduction

The ever increasing need for food to support the growing population of India demands a systematic appraisal of the soil and climatic resources to frame an effective and alternative land use plan. Since the soils and climatic conditions of a region largely determine the suitability for different crop types, the mapping of agro-climatic regions will contribute to identify suitable crops and to develop suitable cropping patterns for increasing the agricultural production on a sustainable basis. An agro-climatic zone is defined here as a land unit that is more or less homogeneous in terms of climate and soil, and that is suitable for a certain range of crops and cultivars. Techniques for estimating the 'agro-climatic' potential of land under tropical climates are usually based on mean monthly rainfall totals (Papadkis, 1966; Oldeman, 1975). A simple method based on rainfall and potential evapotranspiration for deriving variables to classify the semi-arid tropics into relevant agronomically homogenous zones was suggested by Reddy (1983). More recently, other methods have been used, such as water balance models (McCaskill & Kariada, 1991). Such models can utilize either mean monthly rainfall sums, or weekly or daily rainfall data. An approach to calculate the water balance and to identify the potentials for rainfed crop production with the help of a Geographical Information System (GIS) was reported by Thomas (1992). McCaskill & Kariada (1991) suggested that the monthly sums of mean rainfall could be used to interpolate between locations chosen for water balance analysis. The calculation of the water balance in rainfed areas is a difficult procedure because it depends both on the amount and distribution of rainfall, which vary considerably from year to year.

In this paper, the use of a water balance approach will be illustrated in the zonation of production potential of rainfed rice in the state of Tamil Nadu in southern India. In Tamil Nadu, many different crop types are grown, with irrigated rice as the most important cereal crop (especially in the eastern part). Rainfed rice production is practiced only to a minor extent. Plans to increase rainfed rice production in areas having no means of irrigation has lead to the need to identify agro-ecological zones of different capability.

Material and methods

A profile of Tamil Nadu

The Indian state of Tamil Nadu lies between 8° 5' and 13° 5' northern latitude and 76° 15' and 80° 20' eastern longitude (Figure 1). It has a long coast line of about 1000 km length. The western edge of the state is formed by a mountain range called the Western Ghats,

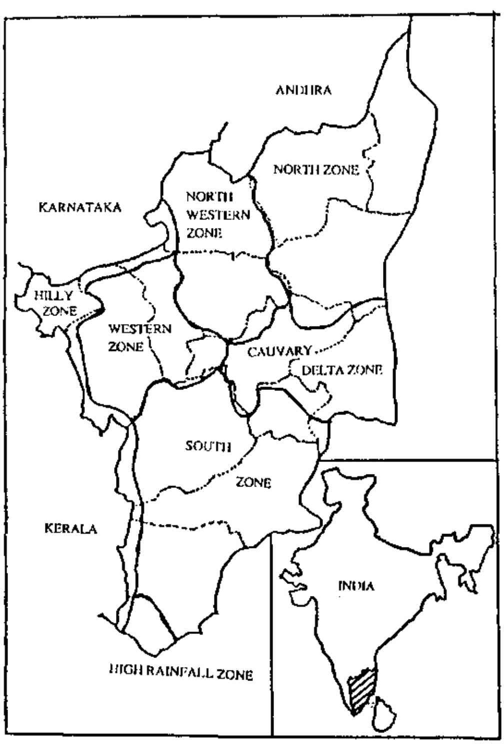

Figure 1. Map of Tamil Nadu (southern India) with the major agro-ecological zones.

which raises at places to over 2000 m ASL (metres above sea level). Almost the entire eastern part of the state is below 150 m ASL. The area of the state is 130.069 km^2. The climate of Tamil Nadu is mostly semi-arid except for a narrow coastal strip that is dry sub humid. The most important feature of the climate is the north-east monsoon (October to December). The average annual rainfall is 1010 mm which falls in 54 rainy days. The monsoon as well as the annual rainfall show large fluctuations from year to year and there is no significant evidence of any trend or periodicity in the rainfall distribution. Considered in relation to crop production, the total annual or seasonal amount of rainfall is less important than the distribution of rainfall during the growing period of the different crops (Subramanian & Kulandaivelu, 1986). The annual maximum temperature generally varies between 31 and 34 °C. May is the month of maximum temperature, except for the coastal areas where June is the hottest month. The annual minimum temperature generally varies between 21 and 26 °C, with January being the coldest month of the year. The annual potential evapotranspiration (ET) varies between 1600 and 2100 mm. In the rainy months of October and November, monthly ET is 100 - 160 and 90 - 140 mm, respectively.

Based on the above climatic factors, Tamil Nadu has been classified into seven agro-climatic zones (Figure 1). The soil types of Tamil Nadu have extensively been described by Palaniappan et al. (1993; this volume).

The water balance method

Subramanian & Kulandaivelu (1986) have found in several regions of Tamil Nadu that estimates of potential evapotranspiration (ET) by different empirical equations, and their closeness to experimental values, differed not significantly. Hence the choice of the method of estimating ET depends mainly on the availability of input data. Here, the Blaney-Cridle method was used that needs only measured air temperature and estimated data for humidity, wind speed and sunshine duration (Doorenbos & Pruitt, 1977):

$$\mathrm{ET}_0 = C\,[\,P\,(0.46T + 8)\,] \qquad (1)$$

where

ET_0 is the reference crop (potential) evapotranspiration for the month considered (mm),

T the mean daily temperature in °C,

P the mean daily percentage of total annual day time hours, and

C is an adjustment factor which depends on minimum relative humidity, sunshine hours and daytime wind speed estimates.

The (potential) evapotranspiration of a real crop, ET_{crop} (mm), is calculated from:

$$\mathrm{ET}_{crop} = \mathrm{ET}_0 \bullet K_c \qquad (2)$$

where

K_c is a crop coefficient (-).

Here, K_c values for different phenological stages of the rice crop were taken from Doorenbos et al. (1979). The water balance is then calculated on a monthly basis, using the formula

$$ASW_m = ASW_{m-1} + ER_m + ET_{crop, m} \tag{3}$$

where

ASW is the available soil water (mm),

ER the effective rainfall (mm), and

m is the running index of the month.

If ASW in a given month is negative, the plant suffers a water deficit. Finally, the yield index Y (%) is determined as the running sum of the monthly water deficits that are expressed as a percentage of the total crop water requirement of the entire season (TWR):

$$Y_{i, m} = Y_{i, m-1} + (ASW_m / TWR) \bullet 100 \tag{4}$$

The yield index is initially 100% and remains at this value until there is a water deficit, when it is decreased by the percentage deficit as a fraction of the total (seasonal) water required. Available soil water that is stored before the growing season can contribute to a significant degree to the water balance. To include this, the calculation of Y_i should be performed for the preceding months a assuming K_c value of 0.3 for the fallow period as suggested by Frère & Popov (1979).

Water balance input data

For Tamil Nadu, the history of rainfall records shows that the start of the season is generally in the second fortnight of September. Therefore, 15 September was taken as the sowing date. The meteorological parameters were collected from 115 stations at the taluk level and grouped into 16 'meteorological' zones based on similarities in e.g. distribution and other aspects. The effective rainfall (ER) was worked out based on a balance sheet method as suggested by Misra & Ahmed (1987). This method takes into account the actual moisture content of the soil and the maximum water holding capacity. The maximum water holding capacity depends on the soil type and varies between 60 - 150 mm in Tamil Nadu. The yield index Y_i was calculated for each mapping unit obtained by overlaying the 16 meteorological zones over a soil map. The yield index values were used as a (indicative) suitability classification.

Results and discussion

The water budget at different times of the growing season can give some important information which might be overlooked when considering only the water balance at the end of the season. Water deficits at different growth phases of the crop have different magnitudes of effects on crop growth. Therefore, the yield index was tracked here on a monthly basis from the beginning to the end of the growing season (north-east monsoon).

In general, the zonation of Tamil Nadu based on the calculated yield indices resulted in different boundaries than those based on major climatic parameters like rainfall, temperatures and ET. Instead, soil type and maximum water holding capacity of the soils were the major source of differentiation. For example in the northern zone, which is based on homogeneity in climatic parameters, the coastal alluvium and river alluvium soils were 'highly suitable' for rainfed rice whereas the red loam soils were only 'moderately suitable' based on the calculated yield indices. In the coastal areas of the northern zone, the soil was comparatively wet at the start of the north-east monsoon season. In these areas, the growing season generally began with a positive water budget and the yield index remained at 100% up to December (Figure 2). The soil moisture content remained fairly high during the growing season but it never reached the maximum level. Though the ET values were high in the early months i.e. July and August before the start of the monsoon season, they were reduced considerably in September and October. In the southern zone, the coastal alluvium and river alluvium soils had a yield index of 70 - 90% and were classified as 'suitable'. The red sterile soils and red sandy soils were 'not suitable' due to the small amount of rainfall and the high atmospheric demand (Figure 3). In the extreme south, the high rainfall zone was 'suitable' because this zone is dominated by both the south-west (June - September) and the north-east monsoon (October-December). Because of the considerable amount of rainfall in the south-west monsoon season, the soil moisture content at the start of the north-east monsoon season was relatively high, which is favourable for a good crop establish-

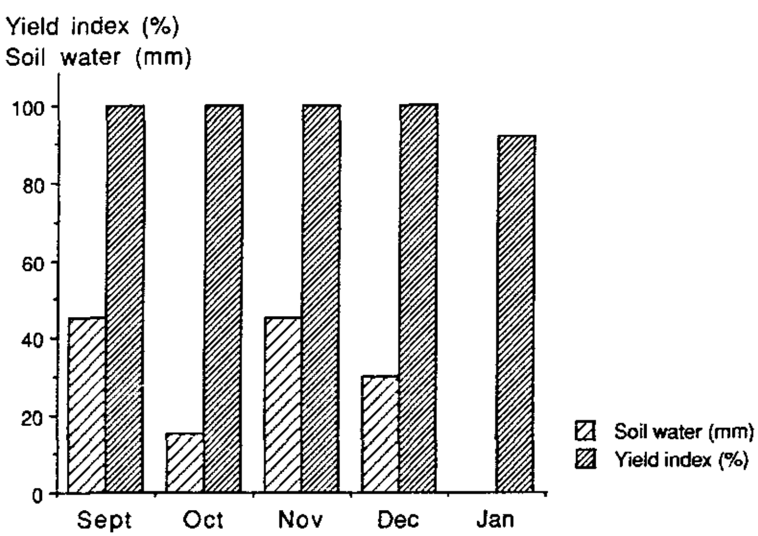

Figure 2. Calculated monthly yield index and soil water content of red loam soils under rainfed rice in the northern zone of Tamil Nadu.

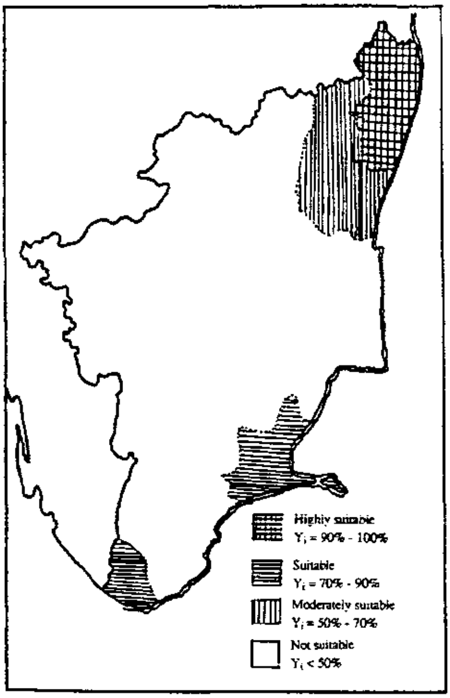

Figure 3. Calculated yield index and indicative suitability classes for rainfed rice in Tamil Nadu, based on the water balance approach.

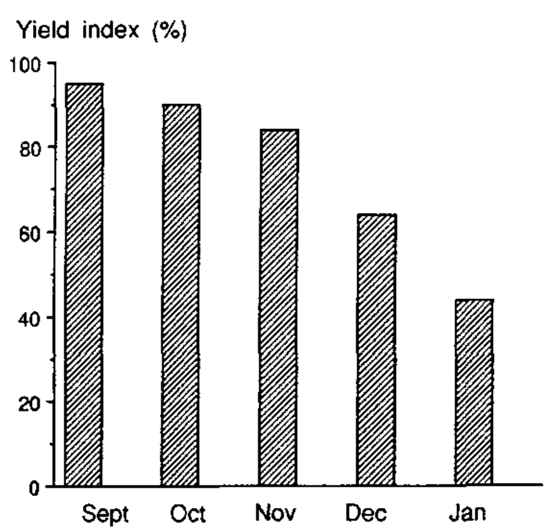

Figure 4. Calculated monthly yield index of rainfed rice on red loam soils in the north-western zone of Tamil Nadu.

ment. In the coastal Cauvery delta zone actual cropping is entirely dependent on canal irrigation. For rainfed rice, it was classified as 'not suitable'. In reality, some small areas in the Cauvery delta zone are actually suitable for rainfed rice. In our study, these small areas were not detected because of the grouping of the input data into larger zones.

In all the interior zones, like the north-western and western zone, the yield index dropped below 50% and these zones were classified as 'not suitable' for rainfed rice cultivation. In these zones a water deficit already existed in the early months of the growing period. A water deficit remained throughout the growing season, which affected crop growth in the drought-sensitive stages of tillering and flowering. In the thin red soils and red loam soils of the north-western zone, not even a single month had a positive yield index due to the high atmospheric demand coupled with low rainfall amounts (Figure 4). The hilly zone of the north-western zone was not included in this classification because rainfed rice cultivation is impossible here (farmers grow high value plantation crops).

Conclusions

The results of agro-ecological zonation using the water balance method, show that soil characteristics/soil types are important variables next to climatic parameters in the suitability assessment of land for rainfed rice cropping. This emphasizes the need for a valid classification method based on a water balance approach in the semi-arid and/or tropical climates. The zonation and suitability classification derived in this study does not automatically exclude areas classified as 'not suitable' from being potentially high yielding regions, as irrigation has not been taken into account.

So far, the water balance approach used in this study has only indicated qualitatively areas that are suitable for rainfed rice cropping. No quantitative indications of rice yield that might be realized were calculated. In this respect, crop growth simulation models can be useful tools in predicting quantitatively potential production levels on regional scales.

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Rice yield potential in different agro-climatic zones of Tamil Nadu, India - a simulation study

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Abstract

A simulation study was carried out to predict the yield potential of irrigated rice at six locations in Tamil Nadu, India, which are situated in different agro-climatic zones. The MACROS model was used to simulate the growth of two varieties, ADT36 and CR1009, in the Kuruvai and Samba season respectively, in 1991 and 1992. In the Kuruvai season, potential rough rice yields varied between 6.5 - 9 t ha^{-1}, depending on location, year and transplanting date. In the Samba season, yields varied between 5.5 - 9 t ha^{-1}, with the lowest yields recorded at Ambasamudram in both years and at all transplanting dates. In both seasons, the optimum transplanting time to produce more than 8 t ha^{-1} yield differed for the six locations and between the two years. The simulated yields showed that the yield loss due to improper transplanting time could be as high as 31%. The total yearly potential production volume in Tamil Nadu was predicted to be in the order of 13 to 16 million tonnes as against the actual 4 to 8 tonnes realized in 1980 - 1990.

Introduction

In Tamil Nadu, India, rice is grown in an area of 1.96 m ha in different seasons, throughout the year. The rice growing seasons have different local names according to the period of transplanting, e.g. Navarai (December - January transplanting), Sornavari and early Kar (April - May), Kuruvai (June), Early Samba, Samba (July - August), late Samba, Thaladi and Pishanam (September - October) and late Thaladi and late Pishanam (November). Nearly 80% of the total rice area is irrigated. Taking up a wetland rice crop is mostly decided by the availability of irrigation water from canals of river systems and from tanks which receive water from seasonal rains. Depending upon the irrigation source and growing season, short duration (100 - 120 days), medium duration (135 - 140 days) and long duration (above 150 days) rice varieties are cultivated. The rice yield potentials in the different seasons, and their corresponding optimum transplanting dates are important research themes of the Tamil Agricultural University. In this paper, the yield potential and optimum transplanting dates of irrigated rice in two important seasons, namely Kuruvai and Samba are studied in different agro-climatic zones of Tamil Nadu, by using crop growth simulation modelling. Total potential production volumes are calculated and compared with actual production volumes in the whole of Tamil Nadu.

Material and methods

Irrigated rice yield potentials in the Kuruvai and Samba seasons were simulated for six locations (research stations of the Tamil Nadu Agricultural University) in different agro-ecological zones of Tamil Nadu (Figure 1):

	Location	Agro-climatic zone
1	Aduthurai (ADT)	Cauvery Delta
2	Ambasamudram (ASD)	Southern
3	Coimbatore (CBE)	Western
4	Madurai (MDU)	Southern
5	Paiyur (PYR)	North-western
6	Tirur (TKM)	North-eastern

A description of the agro-ecological zones is given by Palaniappan et al. (1993; this volume).

The model L1D of the MACROS model (Penning de Vries et al., 1989) was used for the simulation of potential rice yield (i.e. with optimum water and nutrient supply, and without pest, disease or weed infestation). This model has been successfully used to predict the potential yields of rice under different weather conditions (Herrera - Reyes & Penning de Vries, 1989; Jansen, 1990; Dua et al., 1990; Palanisamy et al., 1993). In potential production situations, crop growth is only determined by the weather variables minimum and maximum temperature and solar radiation, and by the characteristics of the crop (variety). In our study, the rice varieties ADT36 (110 days short duration) and CR1009 (155 days long duration) were considered for the Kuruvai and Samba season, respectively. The crop data (carbohydrate partitioning, fraction of stem reserves at flowering, development rate for vegetative and reproductive phases, and development stage at the time planting) were derived from field experiments conducted at Aduthurai with ADT36 (Jeyaraman et al., 1993; this volume) and at Thanjavur with CR1009 (Sivasamy & Thiyagarajan, 1993). The crop parameters were derived from the experimental treatments that resulted in the highest yield. The model was adapted to simulate the actual highest yield obtained by calibrating the maximum rate of leaf photosynthesis from the Aduthurai experiments. All other crop parameters were as in Penning de Vries et al. (1989).

Data on daily maximum and minimum temperature and solar radiation were collected in 1991 and 1992 by the meteorological observatories located at the experimental research stations mentioned above. For these years, potential (rough) rice yields at the six locations were simulated using different transplanting dates: in the Kuruvai season, ten dates from

May 6 to August 4 (day numbers 126 to 216) at 10 days interval, and in the Samba season, ten dates from August 5 to November 3 (day numbers 217 to 307) at 10 days interval.

For comparison with the simulated potential production volumes, actual irrigated rice production volumes in Tamil Nadu were collected from the 'Season and crop reports' for the years 1980 - 1981 to 1989 - 1990 published by the Department of statistics, Government of Tamil Nadu.

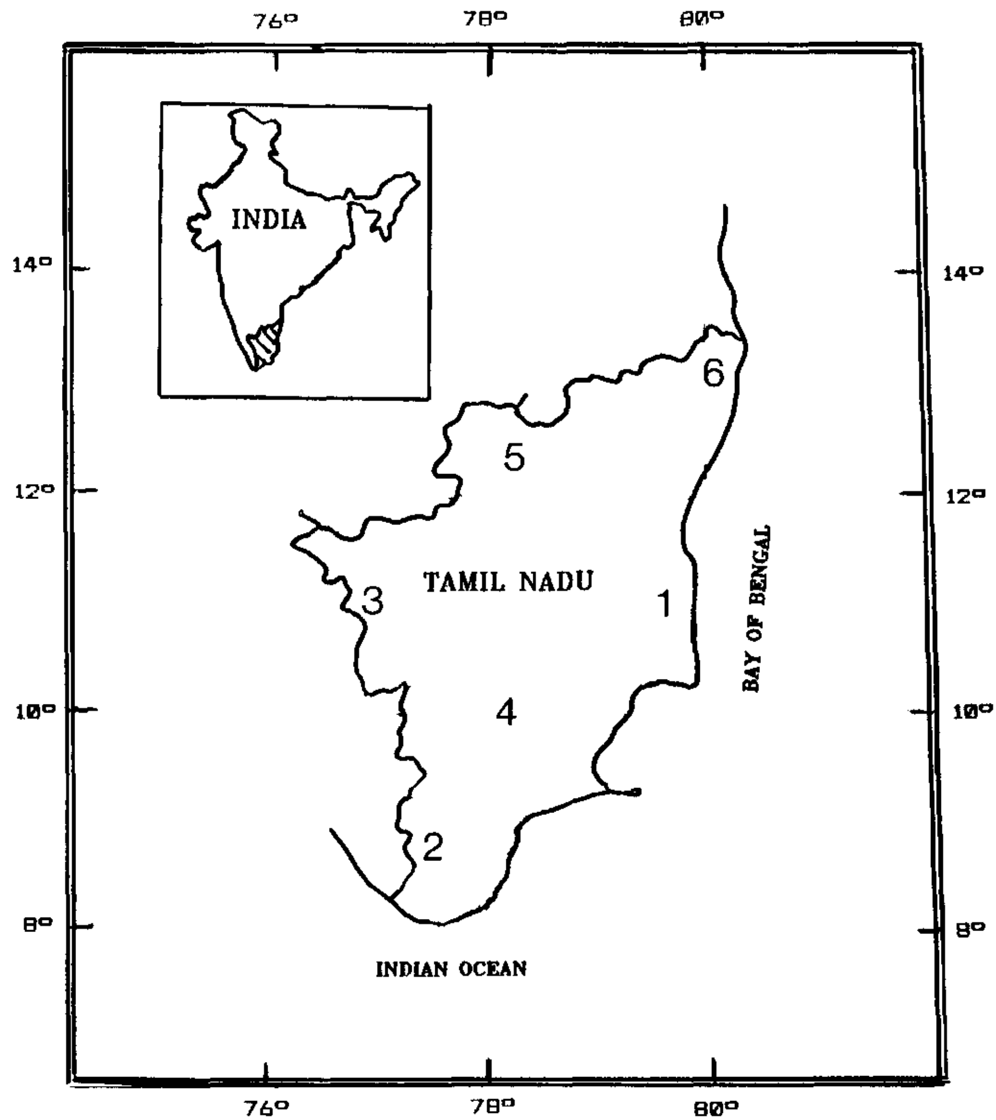

Figure 1. Location of the study sites: (1) Aduthurai (ADT), (2) Ambasamudram (ASD), (3) Coimbatore (CBE), (4) Madurai (MDU), (5) Paiyur (PYR) and (6) Tirur (TKM) in Tamil Nadu, India.

Results and discussion

Weather

The average monthly temperature across all locations showed a steady increase in the maximum temperature from January (30 °C) to May (39 °C) and then a decrease to 34 °C in June (Figure 2). This temperature was maintained until September after which it declined until December. The differences between 1991 and 1992 were very small. The minimum temperature increased from February to May in 1991 and from March to June in 1992, and showed a steady decrease thereafter. The difference between maximum and minimum temperatures was larger between February and May than in the rest of the year.

The mean monthly solar radiation, over all locations, was highest in March, decreased until July and fluctuated thereafter (Figure 2). In 1991, the mean radiation showed a local peak in September. The lowest level of solar radiation was observed from October to December in 1991 and from November to December in 1992. This period corresponds with the middle growth stage of the Samba rice crop. The station of Coimbatore recorded the lowest mean daily radiation while Paiyur recorded the highest.

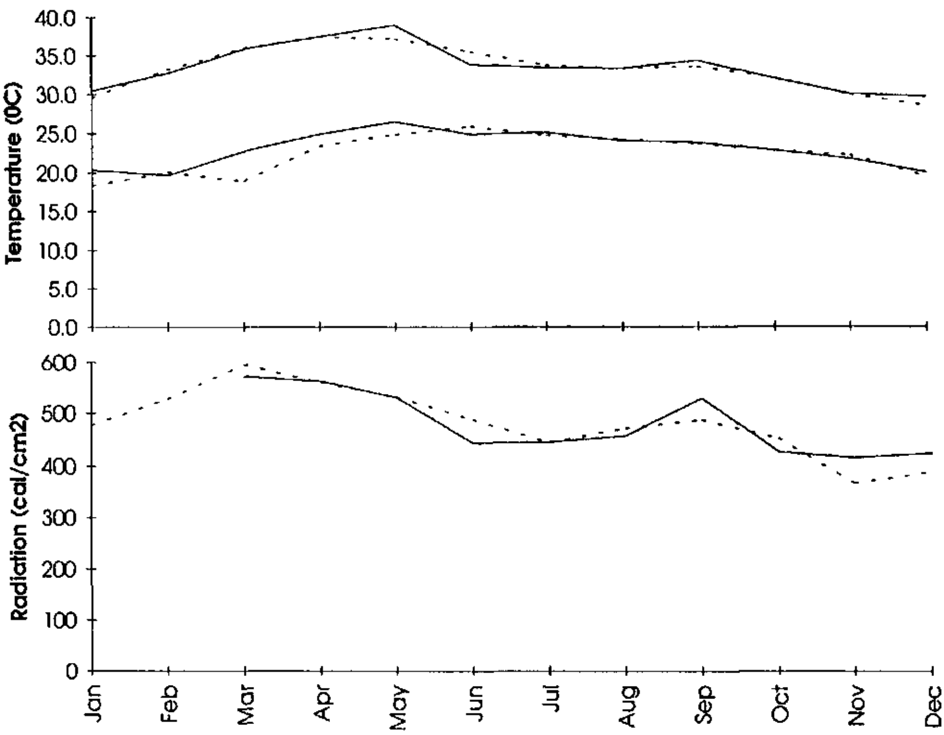

Figure 2. Maximum and minimum temperature and solar radiation (mean for the month), averaged over the six study locations in Tamil Nadu (see Figure 1), in 1991 (solid line) and 1992 (broken line).

Predicted grain yields

Kuruvai season The yield differences between locations was smallest for the June 15 transplanting (day 166) in 1991 and for the July 15 transplanting (day 196) in 1992 (Figure 3). As a period, the yield differences between locations were smallest for the transplantings from May 16 to June 25 (days 136 - 176) in 1991. For the same period in 1992, however, the differences were higher, illustrating the variation in weather conditions between years. A top yield of 9.3 t ha^{-1} was simulated for the August 4 transplanting (day 216) in 1991 at Paiyur, and for the June 15 transplanting (day 166) in 1992 at Coimbatore. The yields were below 8 t ha^{-1} at Tirur in 1992 for all transplanting dates. The results also showed that Paiyur and Coimbatore had a long favourable period for Kuruvai rice growing.

Samba season The simulated yields for the Samba season across the six locations ranged from 6.5 to 8.5 t ha^{-1} in 1991 and from 5.4 to 9.2 t ha^{-1} in 1992 (Figure 4) with different transplanting dates. The Samba season was less productive than the Kuruvai season in Ambasamudram as lower yields were simulated for both years. The yield differences for different transplanting dates at the six locations were higher in 1992 than in 1991 but the maximum yields simulated at all locations were higher in 1992 than in 1991.

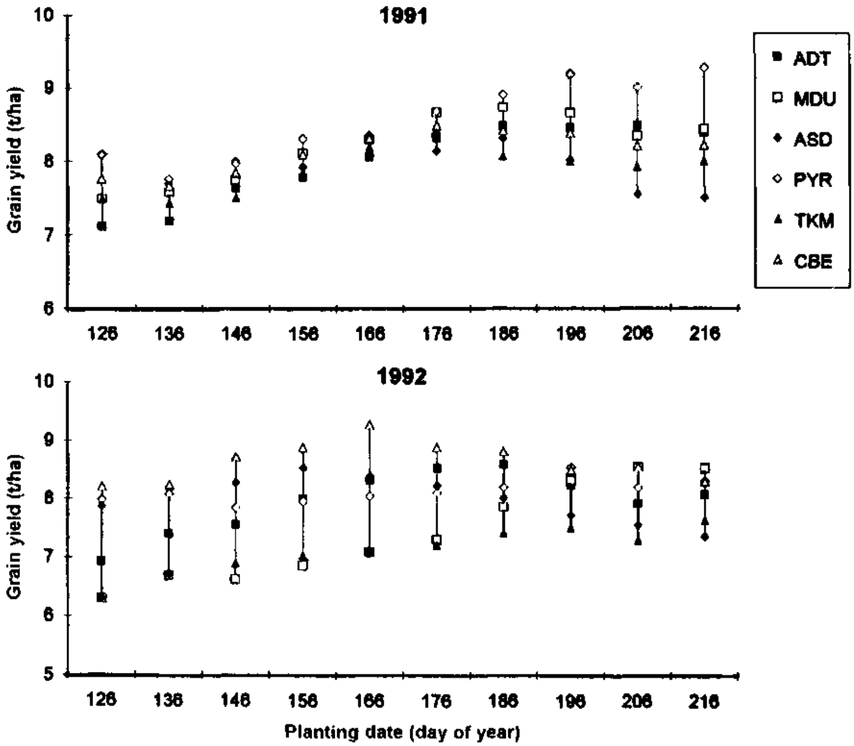

Figure 3. Simulated grain yields of rice for six locations in Tamil Nadu in the Kuruvai season in 1991 and 1992 for different transplanting dates. For abbreviations see Figure 1.

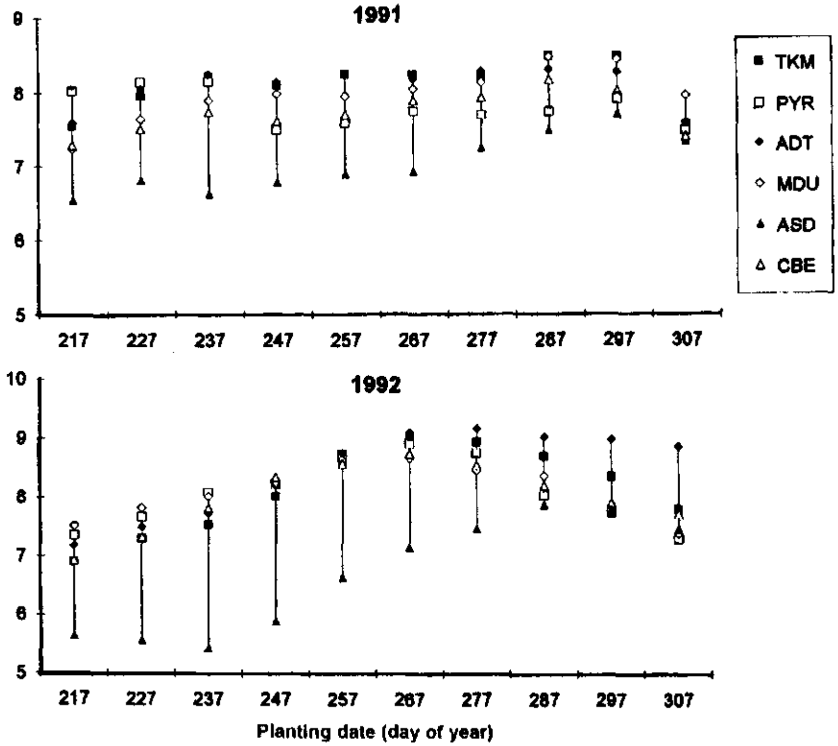

Figure 4. Simulated grain yields of rice for six locations in Tamil Nadu in the Samba season in 1991 and 1992 for different transplanting dates. For abbreviations see Figure 1.

Optimum transplanting time for more than 8 t ha^{-1} yield

Transplanting dates which resulted in potential yields of 8 t ha^{-1} or more in the Kuruvai and Samba seasons for the six locations are presented in Figure 5. In the Kuruvai season, the weather conditions at Coimbatore favoured a transplanting time starting from early May (day 121), while at Aduthurai, the transplanting time started from June 15 (day 166) only. The weather in 1992 was favourable for realizing more than 8 t ha^{-1} yield at all transplanting dates at Coimbatore, but it resulted in less than 8 t ha^{-1} at Tirur. In the Samba season, Aduthurai, Madurai and Tirur had a long favourable transplanting period in both the years. At Paiyur, the transplanting time was in August in 1991 (days 217 - 237), and from August 25 to October 4 (days 237 - 277) in 1992.

The simulated grain yields for the six locations at different transplanting dates showed that, if transplanting was not done at the proper time, the loss in yield could be as high as 31.2% when compared to maximum obtainable yields at optimum transplanting (Table 1). When weather data for more years become available, a fairly reasonable optimum transplanting time for each location can be predicted.

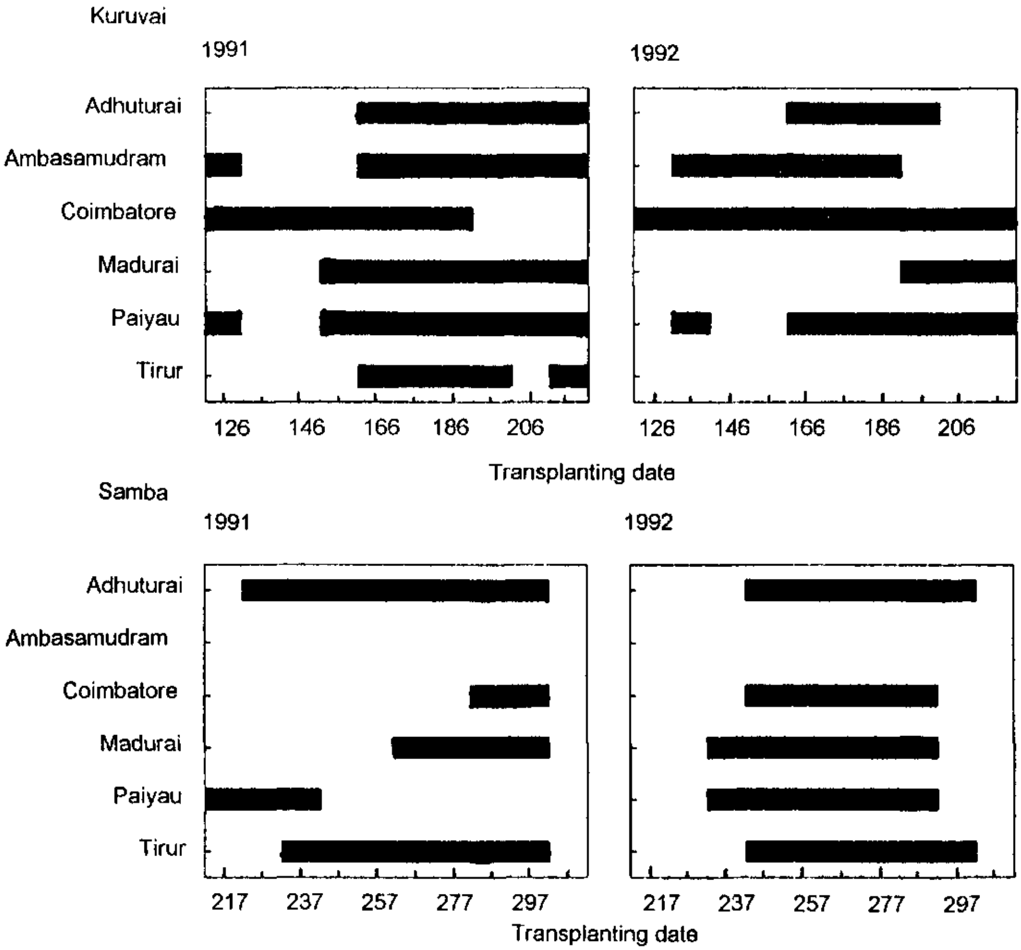

Figure 5. Optimum transplanting dates (simulated yields of 8 t ha^{-1} and more) for the Kuruvai and Samba seasons at the six study locations for 1991 and 1992

Table 1. Percent yield loss of rice yield due to non-optimal transplanting time in the Kuruvai and Samba seasons at the six study locations in Tamil Nadu.

Location	Kuruvai		Samba	
	1991	1992	1991	1992
Aduthurai	16.2	19.4	8.5	22.0
Ambasamudram	10.2	13.7	12.7	31.2
Coimbatore	12.1	11.6	10.9	20.9
Madurai	14.3	27.5	14.6	14.7
Paiyur	16.3	8.3	8.3	18.1
Tirur	10.7	17.3	11.1	23.7

Table 2. Actual irrigated rice area and simulated potential rice production in Tamil Nadu.

S. No	Simulation site	Districts represented	Irrigated rice area[1] (million ha)		Simulated rice production[4] (million tonnes)	
			I crop[2]	II crop[3]	I crop	II crop
1	Aduthurai	Thanjavur Nagai and Milleth Trichirapalli Pudukottai South Arcot	0.572	0.334	3.95-4.92	2.40-3.07
2	Ambasamudram	Nellai Chidambaranar Kanyakumari	0.078	0.070	0.58-0.66	0.38-0.55
3	Coimbatore	Coimbatore Periyar	0.055	0.035	0.43-0.51	0.24-0.31
4	Madurai	Madurai Dindigul Anna Ramanathapuram Pasumpon Thevar Kamarajar	0.190	0.103	1.20-1.65	0.74-0.90
5	Paiyur	Dharmapuri Salem	0.051	0.035	0.40-0.47	0.26-0.31
6	Tirur	Chengai M.G.R North Arcot Thiruvannamalai	0.215	0.146	1.35-1.78	1.01-1.31
		Total	1.160	0.723	7.91-9.99	5.03-6.45

[1] Mean of 10 year data (1980 - 81 to 1989 - 90). Source: Season and crop reports, Department of statistics, Govt. of Tamil Nadu.

[2] Includes Kar, Kuruvai and Sornavari seasons.

[3] Includes Samba and Thaladi seasons.

[4] Computed from lowest and highest yields predicted in 1991 and 1992 for each location for Kuruvai and Samba seasons.

Potential and actual rice production in Tamil Nadu

In Tamil Nadu, actual total rice production in the first season (Kar, Kuruvai and Sornavari together) during the ten year period from 1980 - 1981 to 1989 - 1990 ranged from 0.35 to

4.44 million tonnes. In the second season (Samba and Thaladi), it ranged from 0.87 to 6.59 million tonnes. The actual yield levels in the state have considerably increased from 1.8 t ha^{-1} in 1980 - 1981 to 4.0 t ha^{-1} in 1989 - 1990 in the first season, and from 2.2 t ha^{-1} to 3.0 t ha^{-1} in the second season (Season and crop reports, Statistics Department, Government of Tamil Nadu).

Potential production volumes of irrigated rice were calculated by multiplying the irrigated rice area in the districts surrounding each of the six locations with the simulated potential yield ranges at those locations (Table 2). The simulation results show that the total potential production in the two rice seasons could be in the order of 13 to 16 million tonnes as against the actual 4 to 8 tonnes realized in 1980 - 1990.

Conclusions

- The predicted potential grain yields at the different locations varied considerably with transplanting date.
- The weather conditions that prevailed in 1991 resulted in less fluctuations in yield with different transplanting dates as compared to 1992.
- The weather conditions in Ambasamudram were relatively less favourable for rice cropping in the Samba season.
- Improper time of transplanting could lead to yield losses up to 31%.
- Verification is needed to determine whether the extrapolated predicted yields are correct.
- When weather data for more years become available, a reasonable optimum transplanting time for each location can be predicted.

Acknowledgments

The support of the SARP project in installing radiation integrators at the research stations of the Tamil Nadu Agricultural University in Aduthurai, Ambasamudram, Madurai, Paiyur and Tirur is gratefully acknowledged. The Heads of the research stations/departments at the above mentioned stations are thanked for providing the weather data.

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Effect of weather, transplanting time and plant density on growth and yield of rice; a field study at Aduthurai, Tamil Nadu, India

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Abstract

Two field experiments were conducted at the Tamil Nadu Rice Research Institute, Aduthurai, India, to study the growth and yield of short duration rice in the Navarai (Jan - May) and Kuruvai (June - Sept) seasons, at seven transplanting dates and two plant densities. Rice yield was positively related to maximum and minimum temperatures and to solar radiation during the whole growing season in both seasons in 1992. High minimum temperatures positively contributed to grain yield, whereas high relative humidities negatively influenced grain yield in the Navarai season. The occurrence of high rainfall around 50% flowering negatively influenced grain yield in the Kuruvai season. Higher yields in the Kuruvai season than in the Navarai season were associated with low relative humidity and high minimum temperatures. The transplanting of rice in the second week of February in the Navarai season, and in the first week of July in the Kuruvai season resulted in the highest mean grain yields of 5.7 and 7.7 t ha^{-1}, respectively. Mean grain yields were higher with 80 than with 66 hills m^{-2} (5.1 and 4.4 t ha^{-1}, respectively in Navarai, and 6.8 and 6.2 t ha^{-1}, respectively in Kuruvai).

Introduction

In the Cauvery Delta of Tamil Nadu, India, rice varieties with a short duration are grown in both the Navarai (January - May) and the Kuruvai (June - September) season. The date of transplanting in the Kuruvai season is decided mainly by the receipt of canal water for irrigation (though the crop can also be grown with support from groundwater resources). The transplanting dates in the Navarai season depend on the harvesting of Samba (August - January) and Thaladi (October - January) rice crops and on the availability of irrigation water. The rice crops express their potential yields only under favourable conditions. When there are no water and nutrient constraints, and when the crop is free from pests and diseases, rice yield is only determined by the climatic conditions: potential yield (Kropff et al., 1993; Thiyagarajan et al., 1993, this volume).

The present study was undertaken to find out the influence of weather parameters on the growth and yield of irrigated lowland rice, and to determine the optimum time of transplanting and plant density in the Kuruvai and the Navarai growing seasons.

Material and methods

Two field experiments were conducted at the Tamil Nadu Rice Research Institute, Aduthurai, India (11° N, 79° 30' E and 19.5 m above mean sea level) in the Navarai and Kuruvai seasons of 1992. The soil was classified as Entic chromustert (Soil taxonomy) with a pH of 6.8 and an Electrical Conductivity of 0.6 dS m^{-1}. The rice variety used was ADT36. The treatment consisted of seven planting dates in both seasons: Jan 12, 20, 24, 30, Feb 6, 13 and 21 in the Navarai season, and June 23, 29, July 6, 13, 20, 27 and August 3 in the Kuruvai season. Two plant densities were used, 66 and 80 hills m^{-2} (sub plots). The plant spacings were 15 x 10 cm for 66 hills m^{-2}, and 12.5 x 10 cm for 80 hills m^{-2} in split plot design with three replications. The plot size was 6 x 3.8 m. The weather data were collected from the Agrometeorological Observatory of the Institute. The highest, lowest and mean values of the weather variables are given in Table 1.

Table 1. Highest (H), lowest (L) and mean (M) values of monthly weather data during the growing season of 1992. Maximum and minimum temperatures in °C, solar radiation in cal cm^{-2} d^{-1}, total rainfall in mm, and relative humidity in %.

		Jan	Feb	March	April	May	June	July	Aug	Sept	Oct
Maximum	H	30.4	33.8	38.0	38.7	40.7	39.3	36.4	35.4	35.4	34.0
temp.	L	27.2	29.7	31.8	32.2	30.2	34.5	32.5	32.1	31.6	28.3
	M	28.5	31.7	34.2	36.5	37.4	36.2	34.4	33.4	33.4	31.2
Minimum	H	20.8	22.2	22.6	25.7	26.5	27.4	27.0	26.0	25.0	25.4
temp.	L	16.2	15.4	17.8	20.0	19.6	22.2	21.8	21.0	21.1	21.5
	M	18.1	18.5	13.0	23.1	24.7	29.0	25.1	24.6	23.7	23.6
Solar	H	501	612	637	676	612	587	599	590	609	573
radiation	L	230	437	487	228	180	311	292	250	292	189
	M	446	545	581	553	520	490	466	494	501	446
Rainfall		1.9	-	-	20.0	49.6	159.6	24.4	100.7	123.4	201.2
Relative	H	99	99	100	100	94	99	96	94	98	98
humidity	L	89	93	89	80	65	71	72	75	76	85
	M	96	97	97	90	83	81	81	82	88	92

Table 2. Influence of transplanting date and plant density on growth and yield of rice cv. ADT36 in the Navarai season, 1992. (SE = Standard Error; LSD = Least Significant Difference; ns = non significant).

Transplanting date	Plant height at harvest (cm)	LAI at 50% flowering	Total tillers (m^{-2})	Nos. of panicles (m^{-2})	Nos. of filled grains (m^{-2})	Nos. of unfilled grains (m^{-2})	1000 grain weight (g)
Jan 12	77.3	4.8	376	342	18139	4585	22.5
Jan 20	74.6	4.9	418	384	23772	4357	22.8
Jan 24	78.9	4.9	443	410	24268	4592	22.4
Jan 30	84.3	5.1	455	424	25179	6611	22.1
Feb 6	82.3	5.0	481	424	26214	5496	22.8
Feb 13	89.3	5.2	503	460	29398	6890	21.7
Feb 21	89.2	5.1	415	402	25485	4914	21.0
Mean	82.3	5.0	441	406	24636	5349	22.2
SE	1.21	0.06	8.8	7.4	686.2	160.5	0.26
LSD (P=0.05)	3.73	0.18	27.3	22.9	2114.0	494.6	0.80
66 hills m^{-2}	82.0	4.9	414	378	22595	4901	22.1
80 hills m^{-2}	82.5	5.1	468	433	26678	5798	22.3
Mean	82.3	5.0	441	406	24636	5349	22.2
SE	0.60	0.02	5.9	4.0	306.2	57.5	0.18
LSD (P=0.05)	1.83	0.06	18.1	20.3	928.7	174.4	0.55ns

Results and discussion

The effect of transplanting date and plant density

In the Navarai season, the lowest and highest plant heights were 74.6 and 89.3 cm, and in the Kuruvai season, 90.3 and 100.7 cm respectively (Tables 2 and 3). The mean leaf area index (LAI) was 5.0 in the Navarai season and 5.8 in the Kuruvai season. Shorter plants in the Navarai season might have been due to the low minimum temperatures (Ghose, 1961). The higher LAI in the Kuruvai season might have been due to taller plants (Oldeman et al., 1987).

The mean total number of tillers, panicles, filled and unfilled grains that were associated with the highest yields were 503, 460, 29398 and 6890 when planted in the second week of February in the Navarai season, and 506, 487, 45066 and 4396 when planted in the first

Table 3. Influence of transplanting date and plant density on growth and yield of rice cv. ADT36 in the Kuruvai season, 1992. (SE = Standard Error; LSD = Least Significant Difference).

Transplanting date	Plant height at harvest (cm)	LAI at 50% flow-ering	Total tillers (m^{-2})	Nos. of panicles (m^{-2})	Nos. of filled grains (m^{-2})	Nos. of unfilled grains (m^{-2})	1000 grain weight (g)	Duration from transpl. (d)
June 23	90.3	5.6	447	409	30918	4624	20.7	84
June 29	91.3	5.8	431	418	35436	3764	19.4	85
July 6	91.8	5.8	506	487	45066	4396	19.3	85
July 13	95.3	5.8	479	469	36417	3800	19.2	85
July 20	100.7	5.9	432	413	35375	3530	19.2	85
July 27	98.0	5.9	440	413	30278	3241	19.5	85
Aug 03	96.8	6.0	449	402	29183	2756	19.4	87
Mean	94.9	5.8	455	430	34668	3730	19.5	
SE	0.45	0.38	3.5	8.1	378.1	79.08	0.22	
LSD (P=0.05)	1.38	1.17	10.6	25.1	1164.9	243.7	0.68	
66 hills m^{-2}	95.5	5.7	440	416	32634	3391	19.6	
80 hills m^{-2}	94.3	5.9	470	444	36702	4069	19.5	
Mean	94.9	5.8	455	430	34668	3730	19.5	
SE	0.23	0.03	1.29	3.8	95.9	25.0	0.06	
LSD (P=0.05)	0.69	0.09	3.91	11.5	290.9	75.9	0.18	

week of July in the Kuruvai season (Tables 2 and 3). The number of filled grains increased with later transplanting in the Navarai season, whereas it increased with earlier transplanting in the Kuruvai season. Higher numbers of total tillers, panicles and filled grains m^{-2} in the Kuruvai season than in the Navarai season were caused by high minimum temperatures and low relative humidities (Table 1). The mean thousand grain weight was 22.2 g in the Navarai season and 19.5 g in the Kuruvai season. The higher thousand grain weights in the Navarai season might have been caused by the relatively high radiation intensities after flowering (Oldeman et al., 1987).

Final grain yields varied with transplanting date and plant density in both seasons (Table 4). Grain yields ranged from 3.6 to 5.7 t ha^{-1} in the Navarai season (4.7 t ha^{-1} average) and from 5.6 to 7.7 t ha^{-1} in the Kuruvai season (6.5 t ha^{-1} average). The highest mean grain yield in the Navarai season was obtained with transplanting in the second week of February, and in the Kuruvai season with transplanting in the first week of July. The

Table 4. Influence of transplanting date and plant density on yield of rice cv. ADT36 in the Navarai and Kuruvai seasons of 1992. (SE = Standard Error; LSD = Least Significant Difference).

Navarai season				Kuruvai season			
Transplanting date	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index (%)	Transplanting date	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index (%)
Jan 12	3.6	3.5	49.7	June 23	6.4	6.4	49.8
Jan 20	3.9	3.8	49.8	June 29	6.7	6.5	50.2
Jan 24	4.6	4.5	49.8	July 6	7.7	7.7	50.1
Jan 30	4.8	4.8	50.0	July 13	6.8	6.7	50.3
Feb 6	5.2	5.2	49.9	July 20	6.6	6.7	50.1
Feb 13	5.7	5.6	49.8	July 27	6.0	6.3	48.8
Feb 21	5.4	5.3	50.0	Aug 3	5.6	6.2	47.5
Mean	4.7	4.7	49.9	Mean	6.5	6.6	49.5
SE	0.07	0.04	0.34	SE	0.10	0.12	0.25
LSD (P=0.05)	0.22	0.12	1.00	LSD (P=0.05)	0.31	0.37	0.77
66 hills m^{-2}	4.4	4.4	49.8	66 hills m^{-2}	6.2	6.1	50.1
80 hills m^{-2}	5.1	5.0	49.9	80 hills m^{-2}	6.9	6.8	50.1
Mean	4.7	4.7	49.9	Mean	6.5	6.6	50.1
SE	0.05	0.03	0.11	SE	0.003	0.07	0.14
LSD (P=0.05)	0.15	0.09	0.33	LSD (P=0.05)	0.009	0.21	0.42

relatively low yields in the Navarai season were caused by very low minimum temperatures. Yoshida (1981) has observed rice plant injury with mean daily temperature below 20 °C.

With plant densities of 66 and 80 hills m^{-2}, mean grain yields of 4.4 and 5.1 t ha^{-1} respectively were observed in the Navarai season, and of 6.2 and 6.8 t ha^{-1} respectively in the Kuruvai season. With 66 hills m^{-2}, the highest recorded grain yields were 5.3 and 7.1 t ha^{-1} in the Navarai and Kuruvai season respectively, and with 80 hills m^{-2}, the highest yields were 6.0 and 8.4 t ha^{-1}, respectively. There was only a slight difference in straw yield and harvest index with transplanting date and plant density (Table 4). The straw yield increased with later transplanting in the Navarai season, whereas it increased with earlier transplanting in the Kuruvai season (due to favourable weather conditions).

The effect of weather variables

Correlation analysis between grain yield and weather parameters at different crop growth stages showed that the maximum temperature between transplanting and panicle initiation was positively correlated (r=0.95) to grain yield in the Navarai season, and that the joint effect of maximum and minimum temperature positively contributed (r=0.95) to grain yield in the Kuruvai season. Similarly, the maximum temperature from panicle initiation to 50% flowering was positively correlated to grain yield in the Navarai season (r=0.89), whereas the maximum temperature (r=–0.82) and rainfall (r=–0.76) were negatively correlated with grain yield in the Kuruvai season. However, the interaction of maximum and minimum temperature (r=0.76), rainfall and solar radiation (r=0.79) and rainfall and relative humidity (r=0.86) positively contributed to grain yield in the Kuruvai season.

The minimum temperature (r=0.99) and rainfall (r=0.83) from 50% flowering to harvest positively contributed to grain yield, whereas the relative humidity negatively (r=–0.81) influenced grain yield, in the Navarai season. The interaction of relative humidity with maximum temperature (r=–0.78), and of minimum temperature (r=–0.78) and rainfall (r= –0.91) negatively influenced grain yield in the Navarai season. The joint effect of solar radiation and relative humidity from 50% flowering to harvest negatively (r=–0.95) affected grain yield in the Kuruvai season.

The maximum temperature (r=0.91) and minimum temperature (r=0.83) between transplanting and harvest positively contributed to grain yield in the Navarai season, while the relative humidity negatively influenced grain yield in the Kuruvai season (r=–0.77). The interaction of maximum and minimum temperature (r=0.97), and of rainfall and relative humidity (r= 0.93) positively contributed to grain yield, whereas the joint effect of rainfall and maximum temperature (r=–0.90) and minimum temperature (r=–0.87), and of relative humidity and maximum temperature (r=–0.92) and minimum temperature (r=–0.89) negatively affected grain yield in the Kuruvai season.

In general, high temperatures of 32.5 °C from transplanting to panicle initiation, and of 34.0 °C from panicle initiation to 50% flowering, were optimum for rice yield in the Navarai season. A high minimum temperature of 24.5 °C and low rainfall from 50% flowering to harvest positively contributed to grain yield, whereas high relative humidity (> 91%) reduced grain yield in the Navarai season. High solar radiation (523 cal cm^{-2} d^{-1}) combined with low relative humidity (86%) and low rainfall from 50% flowering to harvest were positively associated with high yields, whereas high rainfall combined with low solar radiation negatively influenced grain yield in the Kuruvai season. Reduction in rice yield due to high rainfall from panicle initiation to harvest might have been due to low translocation of photosynthates from source to sink.

High maximum (34.8 °C) and minimum (20.5 °C) temperatures and high solar radiation (562 cal cm^{-2} d^{-1}) during the whole growing season were found to favour high grain yields in the Navarai season, whereas low relative humidity and low rainfall during the whole growing season were associated with high yields in the Kuruvai season.

Conclusions

The best transplanting time for the rice variety ADT36 in the Kuruvai season was the first week of July, and in the Navarai season it was the second week of February. The Kuruvai season favoured higher grain yields due to higher number of tillers, panicles and filled grains than the Navarai season. In both seasons, a plant density of 88 hills m^{-2} produced higher yields than a plant density of 66 hills m^{-2}.

High minimum temperatures positively contributed to grain yield, whereas high relative humidities negatively influenced grain yield in the Navarai season. The occurrence of high rainfall around 50% flowering negatively influenced grain yield in the Kuruvai season.

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