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Yield Stability of Cowpea Cultivars in Rice-Based Cropping Systems: Experimentation and Simulation

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ABSTRACT

*There is potential in cultivating cowpeas (*Vigna unguiculata* (L.) Walp.) in rice-based cropping systems in the humid tropics as a source of proteins for humans, forage for ruminants, and for improvement of soil fertility. Seasonal and yearly variability is, however, a major constraint. A statistical stability model and a mechanistic simulation model were used to quantify yield variability of early and medium maturity groups of cowpea cultivars in pre- and post-rice environments at Los Baños, Philippines.*

Four field experiments, with 24 cultivars in each experiment, were conducted in pre- and post-rice environments, to determine the response of the cultivars to varying moisture and to water table depth regimes, and a stability analysis was performed across the regimes using a statistical

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model. In the post-rice environment, irrespective of moisture and water table depth regimes, the medium maturing cultivars tended to outyield early maturing cultivars, whereas in the pre-rice environment, early maturity demonstrated a distinct yield advantage.

The statistical stability model indicated that medium maturing cultivars performed well in high-yielding environments, whereas in low-yielding environments their yields were comparable with those of early maturing types. However, results of the statistical stability model are limited because of the short time series of basic data. To broaden the analysis, a simulation model of the cowpea crop was calibrated and validated for its performance. Measured and simulated dry weights of crop parts (leaves, stems and pods) and soil moisture contents at 10-cm soil depths throughout the growing season indicated satisfactory performance of the simulation model. Long-term simulation results using the validated model indicate that TVX1948-012F (medium maturity) performs betters (800–2250 kg ha^{-1}) than IT82D–889 (early maturity) (430–1620 kg ha^{-1}) with a fluctuating shallow water table in the post-rice environment, whereas IT82D–889 is superior (80–1150 kg ha^{-1}) to TV1948–012F (30–1150 kg ha^{-1}) in the pre-rice environment. Yields are highest and least variable for the 15 January planting in the post-rice environment, and for the 15 April planting in the pre-rice environment.

INTRODUCTION

Cropping systems in South and Southeast Asia are predominantly rice based, and cowpea (*Vigna unguiculata* (L.) Walp.) is a promising grain legume for increasing the cropping intensity of rice lands by cultivation in pre- and post-monsoon environments (Carangal *et al.*, 1979). In a global perspective, a yield potential of 4200 kg ha^{-1} has been observed in well-managed cowpea trials in Ethiopia (Nangju *et al.*, 1977). Rainfed cowpea with good crop management produced up to 2700 kg ha^{-1} of seeds in a toposequence dry-season trial in the Philippines (Timsina *et al.*, in press, *a*). Cowpea grown in pre-monsoon environments is constrained by drought caused by low rainfall and a deep water table during the vegetative growth phase and often by excess moisture as a result of high rainfall and a high water table during the reproductive phase. Cowpea grown in post-monsoon environments is constrained by excess moisture during the vegetative phase and drought during the reproductive phase. Contrasting rainfall and water table regimes in the pre- and post-rice environments result in yield instability of cowpea cultivars over seasons and years. An important aspect in evaluating the suitability of any crop for any location is the stability of its performance over seasons and years. Identification of stable cultivars that perform well in the pre- and post-rice environments is an important step in increasing the cropping intensity and improving the productivity of farmers of tropical and subtropical Asia.

One approach in studying this problem is to compare cultivar performance under a range of conditions in the field using growth analysis (Timsina *et al.*, submitted, *b*; in press, *b*) or statistical stability models (Finlay & Wilkinson, 1963; Eberhart & Russell, 1966). Stability models describe cultivar performance in a series of environments based on the results of field experiments, and help determine the yield stability of a cultivar. Field experiments at several sites and seasons are required for such analysis. Another approach to determine yield stability is to explore growth and production for many growing seasons with a crop simulation model. Field experiments are, however, necessary for calibration and validation of the model. Simulation models can help estimate crop growth and yield for different sites, seasons and years from documented theory and data (Penning de Vries, 1982; Whisler *et al.*, 1986; Penning de Vries *et al.*, 1989). We therefore expect that field experiments, for a few seasons and years, along with simulation, should permit a thorough quantitative analysis of yield stability of crop cultivars over long time series.

The objectives of this study were: (1) to perform the yield stability analysis of a range of cowpea cultivars by using a statistical stability model, (2) to calibrate and validate a mechanistic simulation model and (3) to determine the stability of grain yield of TVX1948–012F, a representative medium maturing cultivar, and IT82D–889, a representative early maturing cultivar, in pre- and post-rice environments at Los Baños, Philippines.

A companion paper compares simulated biomass and seed yield response of these cultivars at three climatically different locations in the Philippines (Timsina *et al.*, 1993, this issue).

TRADITIONAL EXPERIMENTAL APPROACHES

Field experiments

Four field experiments were conducted at blocks UB3 (bunded lowland rice field) and UD4 (a sloping upland field) for the experimental farm of the International Rice Research Institute (IRRI, 14°17'N, 121°15'E, 23 m elevation), Los Baños, Laguna, Philippines, from December 1986 to May 1988. In the UB3 field, the soil was an isohyperthermic, clayey, typic tropudalf with a fluctuating shallow to medium water table (0·52–1·32 m

TABLE 1
Important Properties of Upper and Lower Soil Profile at the Experimental Sites

Soil depth	*K (cm day^{-1})*	*Bulk Density (g cm^{-3})*	*Texture*	*pH*	*Organic C (%)*
UB3					
0–10	1·41	1·13	Silty clay	6·7	0·76
10–20	2·23	1·20	Light clay	6·7	0·42
80–100	59·7	0·93	Loam	6·4	0·10
UD4 (SWT site)					
0–20	5·0	1·21	Clay loam	5·8	1·15
80–100	3·2	1·01	Clay loam	6·1	0·27
UD4 (MWT site)					
0–20	28·7	1·22	Silty clay loam	5·6	1·24
80–100	3·74	1·33	Loam	6·1	0·20
UD4 (DWT site)					
0–20	75·0	1·26	Silty clay loam	5·5	1·18
80–100	4·3	0·96	Clay loam	5·6	0·42

K—Saturated hydraulic conductivity; SWT—shallow water table; MWT—Medium water table; DWT—Deep water table.

below soil surface) caused by flood irrigation of rice in adjacent areas. The toposequence in UD4 was a typic tropudalf. Details of the physical measurements of the upper and lower soil profile of the experimental sites are presented in Table 1.

Twenty-four cowpea cultivars were selected, based on the maturity date and economic use. Of these cultivars, five represented early maturing grain types (55–60 days), six early maturing vegetable types (55–65 days), six medium maturing grain types (65–75 days) and seven medium maturing dual-purpose (grain and forage) types (65–80 days) (Table 2, and Table 4 below). Four cultivars, CES41-6, LBBS No. 1 (Los Baños Bush Sitao No. 1), BS6 [(LBBS No. 1*COI) 4–2–1–2], and ALL SEASON, originated from the University of the Philippines at Los Baños (UPLB). All other cultivars were obtained from the International Institute of Tropical Agriculture (IITA) through the Rice Farming Systems Program (RFSP), IRRI.

The cultivars were screened under three moisture regimes in lowland pre- and post-rice environments during 1986–1987, using a line source sprinkler irrigation system. Line-source irrigation creates a gradient of simulated rainfall regimes (Hanks *et al.*, 1976). The same cultivars were screened under a range of water table regimes along the toposequence in the dry season of 1986–1987 and in the wet season of 1987. A naturally

TABLE 2
Mean Seed Yield (kg ha^{-1}) Response of Four Groups of Cowpea Cultivars to Varying Moisture Regimes and Water Table Depth Regimes in Various Growing Situations

Cultivar group	*Post-rice regime, 1986–1987*			*Pre-rice regime, 1987*		
	Fully saturated	*Wet*	*Unirrigated*	*Full ET*	*Partial ET*	*Unirrigated*
Early maturing (grain)	250	350	470	1 110	840	580
Early maturing (vegetable)	210	310	390	430	310	260
Medium maturing (grain)	460	450	730	950	700	509
Medium maturing (dual-purpose)	460	650	920	750	550	400
Cultivar group	*Dry season, 1986–1987*			*Wet season, 1987*		
	SWT	*MWT*	*DWT*	*SWT*	*MWT*	*DWT*
Early maturing (grain)	770	1 040	1 180	360	530	630
Early maturing (vegetable)	460	780	1 170	200	380	460
Medium maturing (grain)	1 060	1 920	1 750	480	810	1 030
Medium maturing (dual-purpose)	1 280	2 020	1 670	450	590	790

ET—Evapotranspiration; SWT—shallow water table; MWT—medium water table; DWT—deep water table.

occurring toposequence creates a gradient of water table regimes that simulates an array of landscape positions with a single rainfall regime (Moya & O'Toole, 1976; Mambani & Lal, 1983). All experiments were conducted in a strip plot design. Experimental details, layout, and crop environment have been discussed elsewhere (Timsina, 1989).

Seed yield responses of the 24 cultivars to varying moisture regimes in the pre- and post-rice experiments, and those for dry and wet season toposequence experiments have been discussed elsewhere (Timsina, 1989). To provide a general overview, we present here the mean seed yield of the cultivars as a group, for varying moisture and water table depth regimes (Table 2). Seed yields of the cultivars responses negatively to the irrigation gradient in the 1986–1987 post-rice, as opposed to their positive response in the 1987 pre-rice environment.

In the 1986–1987 dry season toposequence experiment, seed yields of the medium maturing cultivars as a group were highest for the medium water table (MWT) site, whereas those of early maturing types were highest for the deep water table (DWT) site. In the 1987 wet season toposequence experiment, seed yields of all cultivars as a group were much lower than in the dry season, and all groups produced highest seed yields for the DWT site. Readers should refer to Timsina *et al.* (submitted,

TABLE 3
Stability Analysis of Variance for seed Yields in Cowpea Planted under 12 Moisture Regimes.

Source of variation	*DF*	*Sum of squares*	*Mean square*	*F*
Cultivar (C)	23	23 581 476	1 025 281	16·5**
Env + (C × Env)	264	63 567 785		
Env (linear)	1	39 901 069		
C × Env (linear)	23	9 767 876	424 690	6·8**
Pooled deviations	240	14 898 840	62 078	11·8**
IT82E-18	10	685 015	68 501	13·0**
IT82E-16	10	357 521	35 752	6·8**
IT82D-889	10	715 337	71 533	13·5**
CES41-6	10	848 468	84 846	16·1**
IT82D-892	10	512 110	51 211	9·7*
TVX3236-01G	10	1 654 909	165 490	31·5**
TVX2907-02D	10	910 273	91 026	17·3**
VITA 4	10	563 430	56 343	10·7*
IT82D-716	10	669 974	66 997	12·7**
IT81D-1205-174	10	263 460	26 346	5·0**
ALL SEASON	10	233 264	23 326	4·4**
TVX2724-01F	10	671 422	67 142	12·8**
TVX1948-01F	10	610 283	61 028	11·6**
TVX3381-02F	10	1 295 762	129 576	24·6**
TVX3410-02J	10	781 955	78 105	14·8**
TVX3871-02F	10	172 778	17 277	3·3**
TVX289-4G	10	941 252	94 125	17·9**
TVX1948-012F	10	1 158 0·38	115 803	22·0**
IT81D-1228-10	10	472 594	47 259	9·0**
IT81D-1228-13	10	248 002	24 800	4·7**
IT81D-1228-15	10	97 754	9 775	1·9 ns
FARVE 13	10	128 293	12 829	2·4 ns
LBBS 1	10	315 030	31 503	6·0**
BS 6	10	592 803	59 280	11·3**
Pooled error	288	302 8942	5 258	

* Significant at 5% level.
** Significant at 1% level.

b; in press, *b*) for possible causes of the different responses of the early and medium maturing cultivars to varying moisture and water table depth regimes.

Stability analysis

Stability analysis for the cowpea cultivars across the four experiments (12 moisture regimes) was performed using the models of Finlay and Wilkin-

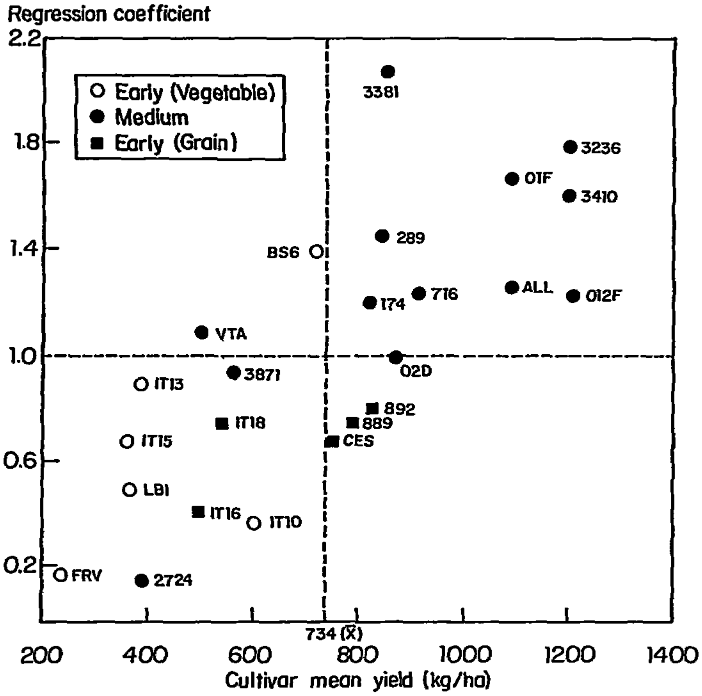

Fig. 1. Relationship between cultivar adaption (regression coefficient) and cultivar mean yield (refer to Table 4 for full names of cultivars).

son (1963) and Eberhart and Russel (1966). A cultivar is defined as stable when it has a high mean yield, a regression coefficient of 1·0, and deviations from regression as low as possible.

The stability analysis of variance for seed yields is shown in Table 3. The analysis of variance partitions the sums of squares due to environments (Env) and cultivars × environments (C × Env) into environments (linear), cultivars × environments (linear), and deviations from the regression model. Pooled deviations of all cultivars except IT81D-1228–15 and FARVE 13 were significant, indicating that there was a high genotype–environment interaction.

Mean (X), regression coefficient (b), and deviation from regression lines (S^2d) for seed yields are presented in Table 4. Regression coefficients and cultivar grand means are plotted in Fig. 1. Cultivars falling in the upper-right quadrant have above average yields and regression coefficients greater than one. These cultivars are from the medium maturity groups and are highly responsive to the environment, producing superior yields under favourable environments. Cultivars in the lower-left quadrant respond less to changes in environment, as their regression coefficients are less then 1·0, with seed yields below average. Except for

TABLE 4
Phenotypic Stability for Seed Yields in Cowpea Planted under 12 Moisture Regimes; Codes Presented in the Table are Used in Fig. 1

Cultivars	*Code*	$\bar{X}$	*b*	S^2d	R^2
Early maturing (grain)					
IT82E–18	IT18	529·3	0·76	63 242	0·58**
IT82E–16	IT16	518·3	0·40	30 493	0·42*
IT82D–889	889	782·6	0·75	66 275	0·56**
CES41–6	CES	740·2	0·66	79 528	0·45*
IT82D–892	892	826·2	0·80	45 952	0·67**
Medium maturing (grain)					
TVX3236–01G	3236	1 209·8	1·81	160 232	0·76**
TVX2907–02D	02D	864·2	0·98	85 768	0·63**
VITA 4	VTA	502·2	1·04	51 084	0·76**
IT82D–716	716	917·1	1·23	61 738	0·79**
IT81D–1205–174	174	825·5	1·21	21 087	0·90**
ALL SEASON	ALL	1 083·6	1·27	18 067	0·92**
Medium maturing (dual-purpose)					
TVX2724–01F	2 724	398·3	0·13	61·883	0·04ns
TVX1948–01F	01F	1 081·7	1·66	55 769	0·88**
TVX3381–02F	3 381	853·0	2·06	124 317	0·84**
TVX3410–02J	3 410	1 185·1	1·62	72 846	0·84**
TVX3871–02F	3 871	564·7	0·93	12·019	0·89**
TVX289–4G	289	849·3	1·45	88 866	0·78**
TVX1948–012F	0 12F	1 208·9	1·22	110 545	0·68**
Early maturing (vegetable)					
IT81D–1228-10	IT10	600·7	0·37	42 000	0·32ns
IT81D–1228–13	IT13	391·2	0·88	19 541	0·84**
IT81D–1228–15	IT15	356·2	0·66	4 516	0·88**
FARVE 13	FRV	242·5	0·18	7 570	0·29ns
LBBS 1	LB1	366·7	0·53	26 244	0·59**
BS 6	BS6	714·7	1·41	54 021	0·84**
$\bar{X}$		733·9			

* Significant at 5% level.
** Significant at 1% level.

two cultivars, VX3871–02F and TVX2724–01F, all other cultivars fall in the early maturity group. They are less adapted to favourable environments, and differ in adaptation to unfavourable environments. Cultivars such ALL SEASON, TVX2907-02D, IT81D–1205–174, IT82D–716, and TVX1948–012F have regression coefficients near 1·0, and mean yields above average, and are considered to be stable cultivars. Among these, ALL SEASON exhibited a relatively low deviation from regression (18 067) with R^2 of 0·92, whereas TVX1948–012F had an S^2d over five times

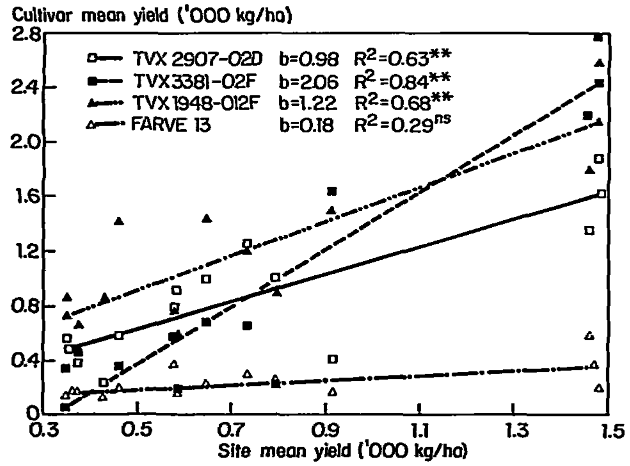

Fig. 2. Relationship between individual yields of four cultivars and site mean yields.

higher (110 545) and an R^2 of 0·68. The other cultivars mentioned were between these extremes. Among the cultivars with the highest mean yield, across all tests (>1200 kg ha^{-1}), which includes TVX3236–01G, TVX3410–02J, and TVX1948–012F, the last had the lowest regression coefficient (b = 1·22), whereas TVX3410–02J exhibited the lowest deviations from regression.

The relationship between individual cultivar means with site mean yields is shown in Fig. 2 for four of the 24 cultivars. TVX2907–02D has a linear regression coefficient of 0·98, indicating average stability. Cultivar TVX1948–012F, on the other hand, has a linear regression coefficient of 1·22, indicating below-average stability, but still produced above-average yields, indicating a broad adaptability. It displayed a strong response in those environments in which site mean yields were high, but also yielded relatively well in trials with a low site mean yields. These are highly desirable attributes of a cultvar released for diverse growing conditions. Vegetable type cultivar FARVE 13 has a very low regression coefficient (b = 0·18) and yielded poorly in all environments, indicating its universally poor adaptability. This cultivar is, however, usually harvested as green pods, as a vegetable, rather than as dry grain. TVX3381–02F is typical of cultivars which are very sensitive to changes in the environment, producing very low grain yield in a low-yielding environment; however the yield increases greatly as the environment improves. Under the most favourable conditions, it is one of the highest-yielding cultivars. This cultivar can, therefore, be described as being specifically adapted to high-yielding environments, and is characterized by a regression coefficient of 2·06, which is significantly greater than 1·0.

TABLE 5
Simulated Seed Yields (kg ha^{-1}) and Evapotranspiration (mm) of Selected Cowpea Cultivars Compared with Observed Data from Experiments

Cultivars	*Seed yields*		*Evapotranspiration*		*Source*
	Simulated	*Measured*	*Simulated*	*Measured*	
Early maturing					
IT82D-889 (Wet reg)	1 002	1 340	226	285	Pandey *et al.* (in press)
IT82D-889 (Dry reg)	861	730	166	150	Pandey *et al.* (in press)
Medium maturing					
IT82D-1137 (Wet reg)	1 745	2 060	341	340	Pandey *et al.* (in press)
IT82D-1137 (Dry reg)	1 147	1 445	265	220	Pandey *et al.* (in press)
EG No. 2 (Wet reg)	1 518	1 440	236	268	Villegas (1982)
ED No. 2 (Dry reg)	1 123	805	150	120	Villegas (1982)

Simple linear regression is also a quantitative measure of phenotypic stability. FARVE 13 shows a high degree of phenotypic stability, implying that the cultivar sustains its seed yield, although low, even in poorer environments (Table 5). TVX3381–02F, on the other hand, is a phenotypically unstable cultivar, with a large deviation from the predicted linear response from trial to trial. TVX2907–02D and TVX1948–012F can be considered as more useful cultivars though their S^2d values are larger than desirable. They have a general adaptability and have maximum yield potential in the most favourable environments. TVX1948–12F is the most preferred cultivar considering its superiority to TVX2907–02D across the range of all site mean yields observed.

Limitations of stability models

Based on the mean yields of cowpea cultivars as a group (across experiments) and as individuals (across 12 moisture regimes) from four field experiments conducted in two seasons at Los Baños, we can draw tentative conclusions regarding the yield stability of the cultivars. The conclusion is that in the post-rice environment, irrespective of water table level, the medium maturing cultivars tend to outyield early maturing cultivars. In the pre-rice environment with a shallow water table, early maturity demonstrated a distinct yield advantage. Most early maturing grain and vegetable type cultivars are poorly adapted to high-yielding environments. Most medium maturing types are adapted to high-yielding environments, with yields comparable with those of early maturing types in the low-yielding environments.

The field experiments provide a measure of the yield stability of the cultivars. However, as the experiments have been conducted for only two seasons at one location, the results are location specific and will be valid only for areas with conditions similar to those of the experiment site. The growth and behaviour of the cultivars differs from season to season and from year to year, as a result of seasonal and yearly variation in weather patterns, and differs greatly depending on water table depth regimes and soil types. Therefore, one cannot generalize the conclusions on yield stability for other seasons, years, and locations. To generalize the conclusions from experimentation, one has to conduct experiments over many seasons, years, and locations, which is almost an impossible task. Thus experiments are necessarily rather limited as far as measuring seasonal and yearly variability of crop yield is concerned.

The question now is: how are we to draw conclusions on the yield stability of the cultivars with a broader validity? The next section on a simulation approach starts with the calibration and validation of a mechanistic simulation model and address more judiciously the issue of yield stability by making use of long-term weather data for Los Baños.

NEW SIMULATION APPROACHES

Model structure

Three modules (L1D, L2C, and L2SS) from MACROS-CSM (Penning de Vries *et al.*, 1989) were combined to simulate cowpea growth and grain yield on soils with impeded drainage. The model, written in Continuous System Modelling Program (CSMP), is largely explanatory and was run on an IBM PC/AT compatible computer. The L1D module simulates crop growth and development processes, using a 1-day time interval of integration. The L2C module simulates transpiration and evaporation. The L2SS module simulates the water balance for crop growth with partially or fully saturated soils, typical for rice-based cropping systems. In the model, daily rates of photosynthesis, respiration, carbohydrate partitioning, phenological development, transpiration, drainage, and movement of water in the soil are computed as functions of the actual status of the crop, of soil water, and of current weather. The model simulates the amount of water contributed by the ground water table through capillary rise. The ratio of crop water uptake and potential transpiration represents degree of water stress. The stress influences photosynthesis, carbohydrate partitioning, and crop development. All rates are integrated at the end of each day to update the weight of the crop organs, and the water contents of the soil layers. The daily cycle is repeated until the end of the growing season is reached. The nitrogen content of crop and soil are not simulated, and are assumed to be optimal.

Model modifications

The following modifications in the original model were made to simulate relevant phenomena in cowpea production on rice lands.

Effect of N-redistribution

The reproductive period is ended by leaf senescence, which in turn is correlated with the redistribution of nutrients, especially nitrogen (N), from the leaves to developing fruits (Eaglesham *et al.*, 1977); Minchin & Summerfield, 1978; Sinclair, 1986). Garcia and Hanway (1976) and Sinclair and de Wit (1975) suggested that leaf senescence is caused by N depletion, brought about by the demands of developing fruits that exceed fixation. Cowpea does no fix N during seed filling (Sinclair *et al.*, 1987). Redistribution of N from leaves to seeds reduces the maximum rate of leaf photosynthesis and causes loss of leaf area (Sinclair & de Wit, 1975; Sinclair, 1986). We assume maximum leaf photosynthesis to decrease progressively during the final 4 weeks at a rate starting at zero and increasing to 0·1 day^{-1} at physiological maturity. Loss of leaf area increases from 0·02 to 0·1 day^{-1} during the final 2 weeks for the same reason.

After-effects of water stress

Water stress is defined as the ratio of actual crop transpiration (= uptake) and the transpiration of the crop with ample water, and may range from 0·0 to 1·0. In addition to the instantaneous effect of water stress through stomatal closure, there is a cumulative effect: the longer stress lasts, the more severe is the effect (van Keulen, 1975). During drought, grain legumes are more stressed by lack of N than by lack of assimilates (Sinclair & de Wit, 1975; Sinclair *et al.*, 1987). This leads to a reduced leaf N content and, consequently, to a lower maximum rate of leaf photosynthesis and accelerated leaf senescence. The rate of loss of leaf photosynthetic capacity was calculated by adding the losses caused by accumulated water stress and accelerated senescence caused by ageing. Losses as a result senescence and ageing are referred to in the 'self-destructive hypothesis' (Sinclair & de Wit, 1975) and are important in grain legumes including cowpea. Loss of leaf weight as a result of ageing and water stress was computed from a running average of day-to-day water stress. Average stress is a running average of the current stress, calculated with a time coefficient of 3 days. Maximum rate of leaf photosynthesis for standard conditions was computed by adding the net difference between its rates of recovery and loss, the value of which increases when drought is relieved at a stress level above 0·8 by 0·1 day^{-1} when leaves are still growing. The rate of leaf senescence is assumed to increase by 0·05–0·1 day^{-1} when the average stress level drops below 0·5.

Experimental results indicate that drought can accelerate the rate of progress to maturity by 25% in cowpea (Alam, 1989; Timsina, 1989). To mimic this effect, the rate of phenological development in the reproductive phase was increased under water stress.

Effects of drought and waterlogging on germination

Failure of germination and poor seedling establishment, as a result of drought in pre-monsoon environments and water logging in post-monsoon environments, are major constraints in growing cowpeas in rice-based cropping systems. Cowpea seeds germinate and seedings grow well when the soil moisture content is above 80% of field capacity (Diputado & del Rosario, 1985). However, when the seeds are waterlogged for 5 days, germination can be as low as 2% (Herrera & Zandstra, 1977). A day was defined as 'wet' when the water content of the top 10 cm of soil was greater than 80% of field capacity but less than 95% of saturation. To simulate germination failure in dry or waterlogged soils, it was assumed that seeds germinate and seedlings establish well only when they experience either 10 consecutive wet days or a total of 15 wet days within 30 days of planting; seeds fail to germinate if they are in dry soil (less than 80% of field capacity) for 30 consecutive days, or if they experience 10 consecutive days of soil water content exceeding 95% of saturation. The soil water profile was simulated for 2 months before planting, to permit evaporation and precipitation to establish a natural balance.

Effects of drought and waterlogging on reproductive growth

When upland crops are flooded during the reproductive phase, growth and seed yield are drastically reduced (Herrera & Zandstra, 1979). Medium maturing cowpea cultivars are more tolerant to waterlogging than early maturing types (Timisina *et al.*, submitted, *a*). To mimic effect of waterlogging during the reproductive phase, it was assumed that cowpea plants are killed when they experience saturated soil for 30 consecutive days (for TVX1948–012F) or 20 consecutive days (for IT82D–889). Growth and seed yield of cowpea are also reduced by drought during the reproductive phase (Pandey *et al.*, in press). To simulate effects of drought, we assumed that plants die when soil moisture is below the permanent wilting point for a total of 30 consecutive days (for TVX1948–012F) or 20 consecutive days (for IT82D–889).

Model calibration

Calibration is adjustment of parameters such that one or more simulation outputs reach a predetermined level, usually that of an observation. Calibration is worth while only when crop and environment are carefully monitored and observation duly recorded, as much time is otherwise wasted in trial-specific curve fitting (Penning de Vries & Spitters, 1991).

The basic structure of the model has been evaluated extensively (Penning de Vries *et al.*, 1989, 1992). Another version, SOYCROS has been developed by Penning de Vries *et al.* 1992, for simulation of soybean in different moisture regimes and land types, including saturated soils. The model can be used for other grain legumes, including cowpeas, with little change in crop parameters and inputs. Readers are referred to that paper for details and a listing of the programs used in the present study. The assimilate allocation patterns of the cowpea cultivars and their initial weights were calibrated using observed weights of crop parts and pod yield for a representative early maturing cultivar (cv. IT82D–889, 55 days) and a representative medium maturing cultivar (cv. TVX1948–012F, 70 days) from carefully executed experiments (Timsina *et al.*, submitted, *a,b*). After calibration, the model overestimated leaf weight of TVX1948–012F throughout the growing season.

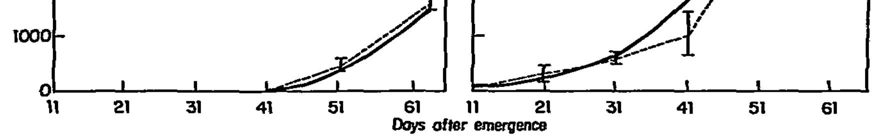

Fig. 3. Simulated and experimental weights (kg ha^{-1}) of leaf, stem, pod, and total shoot of TVX1948–012F in a post-rice environment.

The lower weight of leaves in the experiment may be due to unavoidable experimental error. Simulated stem weights, however, were in agreement with measured weights, except at day 51 (Fig. 3). The model predicted weights of pods and shoots satisfactorily.

Model validation

Validation is the comparison of simulated results with those of experiments that were not used for the calibration. A model is a representation of the real system if it simulates yield for specific situations with the required accuracy and within a specified range of conditions. Hence, it is important to establish the range of applicability of validated models and avoid over-extrapolation of model behaviour (Tsang, 1987). Our model was validated for seed yield, soil moisture content, and evapotranspiration (ET) with the experimental data of Villegas (1982) and Pandey *et al.* (in press). Both experiments were conducted at IRRI, Los Baños, Philippines.

The comparison of measured and simulated soil moisture contents at 10-cm depth over the growing season of TVX1948–012F during the dry season, with the water table depth fluctuating between 0·3 and 1·20 m, indicated satisfactory model performance (Fig. 4). Except for a few days, the model accurately predicted soil moisture contents until 45 days after emergence, and slightly overestimated them after that. This overestimation was probably due to increased fluctuations of the water table depth as the growing season progressed (Timsini *et al.*, submitted, *a*).

Table 5 shows a comparison of simulated seed yields and ET with

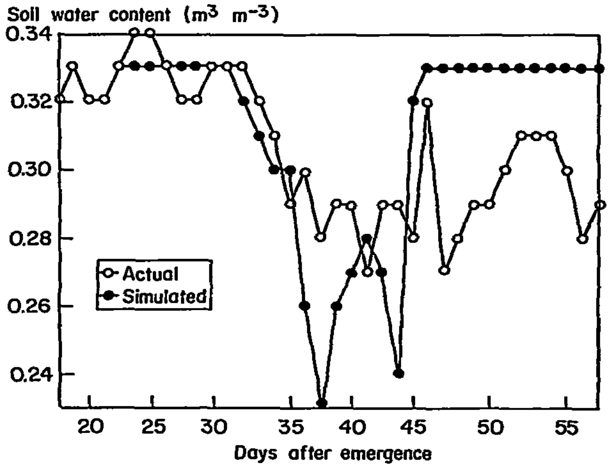

Fig. 4. Simulated and actual soil water contents at 10-cm soil depth when TVX1948–012F cultivar of cowpea was grown in unirrigated treatment.

the data obtained from several independent sets of experiments. The simulated results show in most cases a satisfactory agreement with actual values obtained from the experiments, although actual seed yields recorded for a few situations are higher by 25% (IT82D–1137, dry regime) and by 33% (IT82D-889, wet regime) than those simulated. Measured seed yield of EG No. 2 (dry regime), on the other hand, is 29% lower than the simulated value. Crop data for the present study were taken from TVX1948–012F and IT82D–889, and soil moisture and ground water measurements were made in 1988. Hence, the differences in seed yields may be due to differences it the cultivar characteristics (e.g. number of days to maturity, carbohydrate partitioning, harvest index, etc.) and differences in the soil water conditions prevailing in the experiments of Villegas (1982) and of Pandey *et al.* (in press). We suggest that future experiments should aim at measuring carefully relevant crop data for each cultivar.

Model validation was succeeded by running our model to establish cowpea performance for a long time series at Los Baños (next section)

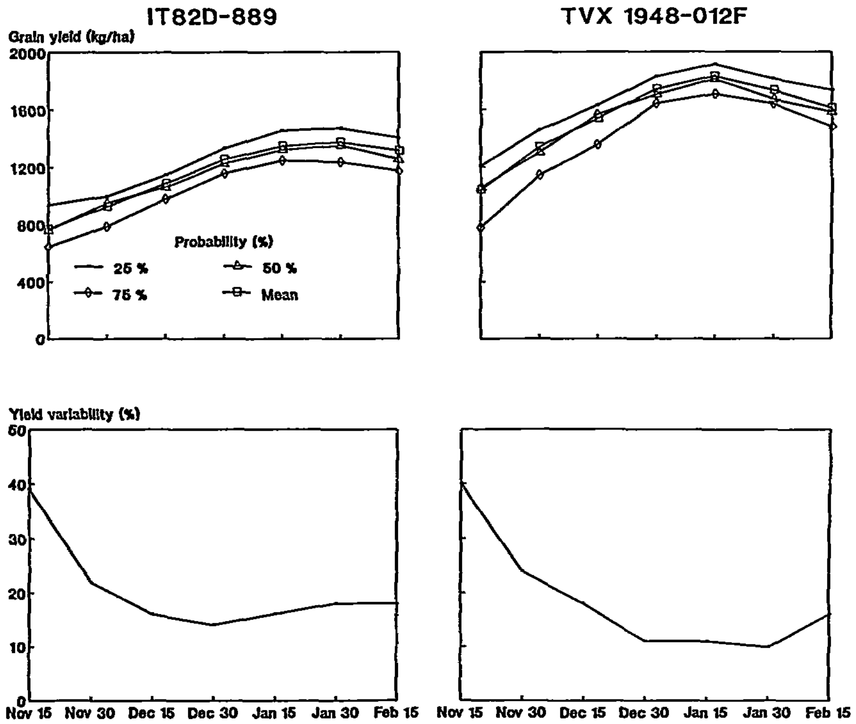

Fig. 5. Effect of date of planting on simulated grain yields of two cowpea cultivars along with corresponding yield variability for fields with a shallow water table and partial irrigation in post-rice environment at Los Baños, Philippines.

and for varying moisture and water table regimes at a range of sites in the Philippines (Timsina *et al.*, 1993, this issue).

Model application

The validated model was run for IT82D–889 and TVX1948–012F for a range of planting dates with 20 years of historical weather data for Los Baños to simulate seed yields and compute yield stability. Yield stability here refers to the difference in yield levels that have a probability of 75% and 25% of being exceeded in any year relative to yield level with 50% probability; the smaller the difference the larger the stability. The choice of the 25 and 75 percentiles is arbitrary; others prefer the 20 and 80 or the 10 and 90 percentiles. It was assumed that there was sufficient water available either from ground water or from rain for germination of seeds and growth of seedlings until 10 days after germination. This simulates the situation where the farmer plants after rain or provides initial irrigation. A companion paper simulates yields for situations where water may

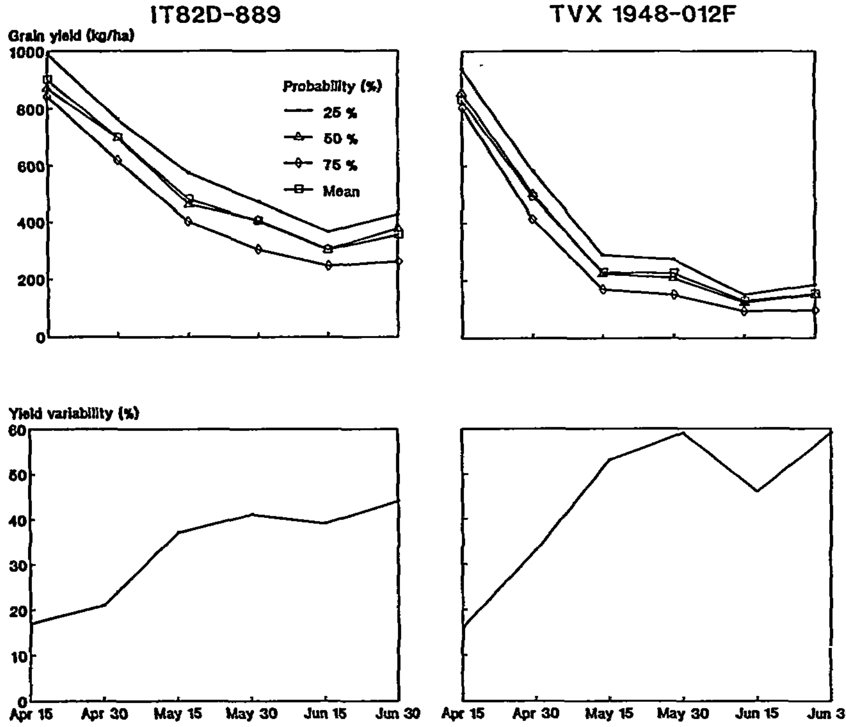

Fig. 6. Effect of date of planting on simulated grain yields of two cowpea cultivars along with corresponding yield variability for fields with a shallow water table and partial irrigation in pre-rice environment at Los Baños, Philippines.

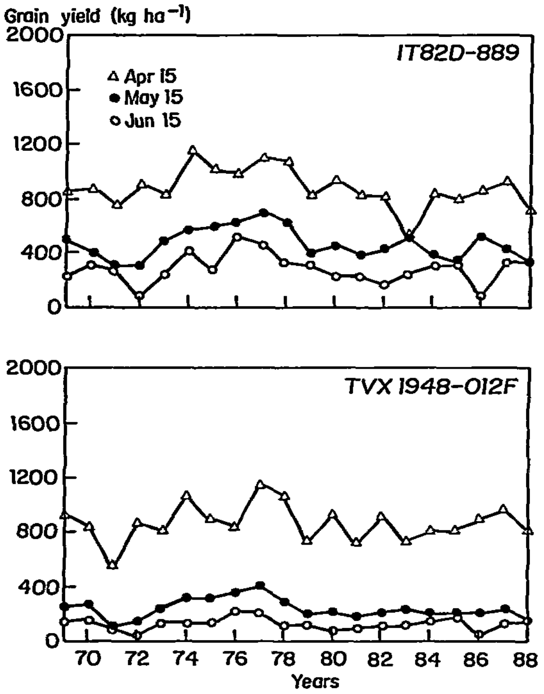

Fig. 7. Year-to-year variation in simulated grain yields of two cowpea cultivars for fields with a shallow water table sown on 15 April, 15 May, and 15 June, in pre-rice environment at Los Baños Philippines.

not be available for germination and seedling establishment (Timsina *et al.*, 1993, this issue).

Simulated grain yields for a range of planting dates and the trend in yield variability as a function of planting date are shown in Figs 5 and 6. In the post-rice environment (Fig. 5) mean yields of the later maturing cultivar (TVX1948–012F) were higher than those of the earlier maturing cultivar (IT82D–889) on all dates. Mean yields of both cultivars were highest on the 15 January planting (1800 and 1300 kg ha^{-1}) and lowest on the 15 November planting (1050 and 750 kg ha^{-1}). After the 15 November planting, yields increased to 15 January, then levelled off or declined. Yield variability ranged from 14 to 40%, with greatest variability for the 15 November planting. In the pre-rice environment, mean grain yields for IT82D–889 were higher then for TVX1948–012F at all dates (Fig. 6), which is the reverse of the post-rice case. Grain yields of both cultivars were highest on 15 April (900 and 800 kg ha^{-1}) and lowest on 15 June (380 and 180 kg ha^{-1}). Yield variability ranged from 18 to 60%, with greatest variability for the 30 May–30 June planting.

The year-to-year variations in grain yield for 15 April, 15 May, and 15 June (during pre-rice environment) are plotted in Fig. 7, and those

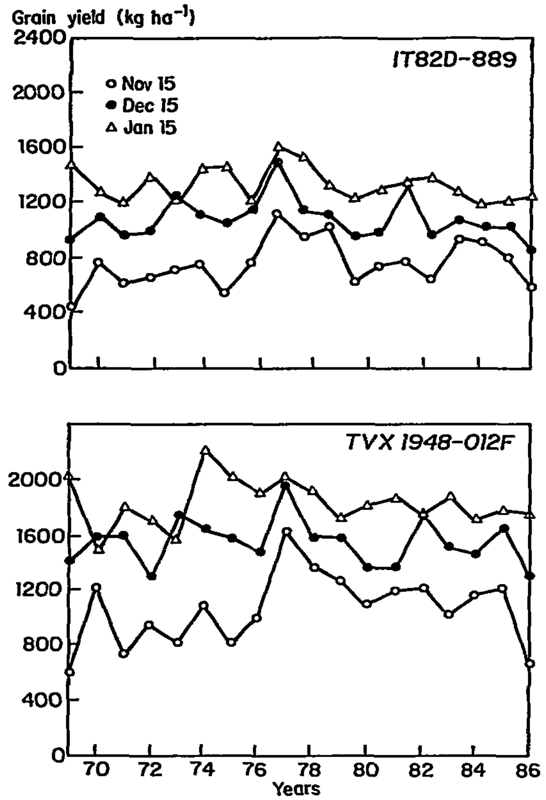

Fig. 8. Year-to-year variation in simulated grain yields of two cowpea cultivars for fields with a shallow water table sown on 15 November, 15 December and 15 January, in post-rice environment at Los Baños, Philippines.

for 15 November, 15 December, and 15 January (during post-rice environment) are plotted in Fig. 8. The yield of TVX1948-012F in the post-rice environment fluctuated between 80 and 2250 kg ha^{-1} and that of IT82D-889 ranged between 430 and 1620 kg ha^{-1}. Yields in the pre-rice environment ranged between 30 and 1150 kg ha^{-1} for TVX1948-012F, and between 80 and 1150 kg ha^{-1} for IT82D-899.

Analysis of the rainfall data indicated that most years had a high and intense rainfall, a high water table, and many cloudy days at the onset of the dry season (November-December) and during the wet season (June-September), which resulted in severe waterlogging in November and June, and consequently increased the variability of grain yields for the 15 November and 15 June plantings. Simulation analysis further revealed that TVX1948-012F performed better than IT82D-889 in the post-rice environment, whereas IT82D-889 was superior to TVX1948-012F in the pre-rice environment. These results are also in agreement with the results of field experiments presented elsewhere (Timsina, 1989).

It should be noted that the simulated yields presented above are rainfed potential yields, and apply to situations where pests and diseases are kept completely under control, and ample phosphorus and other minerals are present.

Complementarity of simulation and experimentation

Experiments and models both have strengths of applications. Experiments were useful to determine the response of the cultivars to moisture regimes (in pre- and post-rice environments) and to water table depth regimes (during dry and wet season toposequence). However, the results are limited because they are location specific and even have a limited applicability for other seasons and years.

Models and simulations are strong on overall yield responses and long-term perspective. A model can provide long-term perspectives of grain yield and quantify yield stability of cultivars. We demonstrated that once a model is validated, it can quickly provide results for other years and different situations. Inaccuracies and uncertainties are, however, unavoidable, and this topic is discussed in greater detail in the companion paper (Timsina *et al.*, 1993, this issue).

CONCLUSIONS

Cowpeas of a seasonal duration of less than 90 days are a relatively recent addition to the repertoire of field crops that may be produced on Asian wetlands in a cropping sequence with rice. There are few data available on cowpea performance in these environments, particularly in response to typical patterns of waterlogging that afflict crops in rice-based cropping systems. This study examined the stability of cowpea performance across a range of water regimes for contrasting post-rice and pre-rice situations. Two analytical methods were applied to the problem—statistical and mechanistic modelling.

Statistical stability modelling indicated that among the sample of cultivars tested, representing early and medium maturity groups, there was a distinct maturity–season interaction. In the post-rice environment of Los Baños, irrespective of water table level, the medium maturity cultivars tended to outyield early maturing cultivars. In the pre-rice environment with a shallow water table, early maturity cultivars demonstrated a distinct yield advantage.

These observations were explored in greater depth with a cowpea simulation model. The simulated results supported those of the field experiments, and, furthermore, allowed a multi-year analysis for estimation of the long-term variability of cultivar-specific yields. The model allows for the investigation and identification of stable cultivars based on multi-year weather data. The cowpea simulation model presented here is aimed at increasing the understanding of researchers, to help them make better choices of cultivars for the different niches of pre- and post-rice growing situations in the rice-based cropping systems of South and Southeast Asia.

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