Water management for mungbean within rice-wheat cropping systems of Bangladesh: a simulation study

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Abstract

To increase crop and soil productivity in rice-wheat cropping systems of Bangladesh, short duration mungbean crops are being considered for the wheat to rice transition period. Due to uncertainties in onset, frequency, and amount of pre-monsoon rainfall, these crops are often damaged by waterlogging, with its incidence and severity exacerbated by the presence of shallow watertables (SWT). This study examined the potential benefits of shallow sub-surface drainage on mungbean performance using the SWAGMAN Destiny simulation model. The model, validated for grain and biomass yields for a site in northern Bangladesh, was used to examine various planting dates and water table scenarios for irrigated mungbean crops. With drainage (at 50 cm depth), yields were greater under a SWT (50 cm), but without drainage, they were greater under a deep watertable (DWT, 500 cm) for all planting dates. In drained fields, the yields were greater for 30 April planting, but when undrained, they were greater for 15 March planting for both watertable scenarios. When crops were rainfed, yields were also greater when shallow drainage was provided. Smaller yields in all scenarios were associated with either high water deficit stress or waterlogging stress. Results indicate that mungbean productivity in rice-wheat systems in Bangladesh could be increased by managing water tables and selecting optimum planting time.

INTRODUCTION

In the intensive rice-wheat (R-W) cropping systems of Bangladesh, there is a window of three to four months for growing a crop after wheat and before the main *T. aman* rice crop planted in July. This pre-monsoonal period is characterized by intermittent but often heavy rainfall events. Some crop alternatives are short- duration transplanted rice (*T. aus*), jute, maize, and mungbean. *T. aus* often has low productivity due to the short growing season, the occasional drought events and the high incidence of diseases and pests due to high rainfall during flowering and grain filling periods. Jute is a feasible option but requires more water and delays the establishment of the main *T. aman* crop. Maize could be grown, but yields are smaller due to the short growth duration period available and the high rainfall during the latter part of the season. All these crops are highly nutrient extractive and in the absence of adequate fertilizer degrades the soil nutrient base of an already intensive system. Mungbeans have distinct advantages in the system due to their short-growth duration and their ability of fixing atmospheric N_2 (Herridge and Bergersen, 1988; Peoples and Herridge, 1990).

The pre-monsoon period, however, has erratic rainfall leading to water deficit stress in some years and waterlogging in others. Waterlogging affects the emergence, establishment, growth and productivity of legume crops (Herrera and Zandstra, 1979;

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Stanley et al., 1980; del Rosario and Pandey 1985; Timsina et al. 1993, 1994). Mungbean is sensitive to both low and high soil moisture (Trung et al. 1985a, b) and is especially vulnerable to excessive rainfall as it approximates maturity (Imrie et al. 1988). The developing seeds rot and decay when hit by intense rainfall, reducing the emergence percentage during consequent cropping. These effects are exacerbated by the presence of shallow water tables (SWTs) in some fields. Mungbeans could be sown in March or April as a post-wheat or pre-rice crop. If they are sown too early, the seeds will not emerge from dry soil. If emergence does occur, the seedlings could suffer from drought stress. In contrast, if sown too late, they could suffer from waterlogging throughout growth, especially during the reproductive period. Damage to the crops, however, depends on the incidence of the pre-monsoon rainfall and the depth of the watertable. In wet periods, SWTs increase the likelihood of waterlogging problems, but in dry periods they are beneficial for meeting part or all of the crop water requirement through upward capillary flux (Ragab and Amer, 1986; Williamson and Kriz, 1970; Hundal and de Datta, 1984; Wallender et al., 1979).

Drainage (surface or sub surface) is one of the strategies for alleviating waterlogging damage to many crops (Doorembos and Kassam, 1979). By providing a zone of soil with adequate aeration, shallow drainage (about 50 cm from the soil surface) could benefit crops during the pre-monsoon season. Choosing an optimum planting date together with appropriate drainage techniques would help alleviate the damage due to waterlogging and SWTs and increase the productivity of mungbean in the R-W system.

Simulation models of soil-crop systems are tools that can help understand crop responses. They can potentially be used to devise water management strategies for the successful cropping of mungbean. This study applies the SWAGMAN Destiny Model for analyzing alternative management scenarios to alleviate the problem of waterlogging and SWTs of mungbean in R-W systems.

METHODOLOGY

The Model

The SWAGMAN Destiny Model (Meyer et al., 1996) has evolved from the SWAGMAN What If program (Robbins et al., 1995) and from experience with the CERES models of crop growth (Ritchie and Otter-Nacke, 1985). It is a one-dimensional (point scale) model that estimates water and salt balances in response to crop agronomy, irrigation management and daily weather conditions. Many of the procedures used in the water balance simulation are derived from the SALUS Model (Ritchie, unpublished, 1999). Operationally it has three inter-linked components: the soil water and crop growth simulation model, a data base for soil, weather, crop and economic parameters, and a shell program which controls simulation, access to the data bases, graphics and programs analysis. The package has three modes of operation. A *continuous detailed mode*, which is most commonly used for model testing with observed data. The second is the *strategic mode*, where the user can select five scenarios associated with a particular variable such as crop type, soil type, water table level, and the salinity of the soil and irrigation water. This mode is used to examine the variability in response to chosen scenarios. The third *continuous multi-year mode* examines the consequences of following a particular strategy as well as trends of water table levels, salinity levels, yields and weather related variabilities (Meyer et al., 1996).

The model calculates zero-to-unity indices for water deficit and waterlogging (lack of aeration) stress. These indices have a value of 1 when the respective conditions do not limit growth and 0 when they fully limit growth. The model simulates daily crop growth, partitioning, and root distribution in the soil profile. The distribution of roots together with the simulated distribution of extractable water throughout the profile is used to determine the potential root water extraction for the day. The model determines potential transpiration from the size of the canopy and meteorological parameters. The ratio between potential root water extraction and potential transpiration is the soil water deficit stress index. The waterlogging stress index is determined by considering where roots are located in the soil, how much of the drainable porosity is filled up with water, and how long it has been wet. When graphed, the two stress indices represent the average values during the growth period. Examination of these indices together indicates the relative magnitude of the major stress effects on yield. The major limitation of the model is that it does not handle the seed quality, which is affected by pre-monsoonal rainfall and is a major constraint of growing pre-rice legume crops.

Calibration

The model can simulate a range of annual crops, perennial pastures, and perennial horticultural crops and requires few inputs that can be readily configured to describe different crops. The model requires input coefficients, which describe the duration of growth from planting to flowering (DDVeg) and from planting to maturity (DDMat) expressed in terms of degree days above base temperature (Base T). The division of the growth phases into pre-flowering and post-flowering phases is used to delineate the stages when LAI is either increasing or decreasing. The canopy growth component of the model requires a potential maximum LAI (Peak LAI) as input. This refers to the LAI that could be attained without limitations of nutrients, water, salinity or aeration.

The parameters used within the model to derive the duration of growth and potential yield were those found appropriate from other data sets. The coefficients or values used were: DDVeg, 900 degree days; DDMat, 1600 degree days; peak LAI, 4; base T, 8°C, and potential yield, 2 t ha^{-1}.

Validation

The model was validated for grain yields of *T. Aman* rice, wheat, maize, and mungbeans in Bangladesh using the data from field experiments conducted in the past (Xevi et al., 1999). For mungbeans, data were derived from experiments conducted during 1984 and 1985 on a salty clay loam soil at the Bangladesh Agricultural Research Institute (BARI), Joydebpur (24°00'N lat.; 92°25'E long.). The crops were rainfed during the pre-kharif season but received substantial rainfall during the season in both years (1212 mm during April, May, and June in 1984 and 810 mm during the same months in 1985). The plots were managed well and drained as necessary. Details of the experimental conditions are presented by Hossain et al. (1990).

Application

The model was used to investigate a combination of a range of water table, irrigation, drainage, and planting date scenarios. Three planting dates (15 March and 7 and 30 April), three initial watertable depths (shallow - 0.5 m, medium - 3.0 m, and deep - 5.0 m), two moisture regimes (irrigation and rainfed), and two drainage regimes (drained and non drained) were chosen for analysis. For drained scenario, a sub-surface shallow drainage was provided to the upper 0.5 m of the soil profile. Drainage into drains occurred when soil water content in that layer exceeded the drained upper limit, and stopped when the maximum drainage rate of any layer in the profile, defined by the parameter KSMACRO, was reached. The chosen sub-surface drainage would be representative of drains dug by farmers, which would carry away drainable water in the upper part of the profile.

All simulations assumed a regional piezometric level of 5 m below the surface with a bottom boundary flux condition set at 0.1 cm d^{-1}. Irrigation was applied to recharge the profile after every 50 mm of evapotranspiration. Piezometric conditions for irrigation management options used in the simulations were representative of cropping systems in the area; detailed observations on these parameters were not available. Soil parameters were estimated from soil texture observations using the procedure described by Ritchie et al. (1999) while actual daily weather data were used for validation.

Model responses were examined using cumulative probability distribution functions (CPDFs) for grain yield, water deficit stress index, and relative aeration stress index using 10 years of weather data. All nutrients, pests and diseases were assumed to be non-limiting factors.

RESULTS

Validation of the model

In normal years, the model simulated rice, wheat, and maize yields in Bangladesh with reasonable accuracy, but in years with cyclonic storms and heavy rainfall it underestimated yields because of losses due to crop lodging and pest damage (Xevi et al., 1999). In both years, however, the model simulated grain yields of mungbeans that were similar to experiments (observed yields of 1.56 and 1.41 t ha^{-1} as against 1.63 and 1.44 t ha^{-1}, respectively for 1984 and 1985). The agreement between the simulated and the observed yields allowed the use of the model to investigate a range of scenarios associated with waterlogging/aeration and water deficit stresses for mungbean crops for inclusion in the rice-wheat sequences of Bangladesh.

Simulated seasonal water table depth

Figure 1 depicts the simulated seasonal fluctuation in water table depth for three different initial water table depths. When the initial depth was near the surface (0.5 m), the water table throughout the season remained near the surface. For the initial water table depth of 3.0 m, there was a rise towards the surface in the later part of the season, while for the initial depth of 5.0 m, there was no change and the water table always remained at 5.0 m. The figure illustrates how severe the water table effect could be under high-rainfall conditions and how badly it could damage crops under those conditions. It also indicates, however, that the SWT could meet crop water requirements especially under rainfed conditions. Such conditions generally prevail in the low-lying 'beel' areas (areas with SWTs) of Bangladesh.

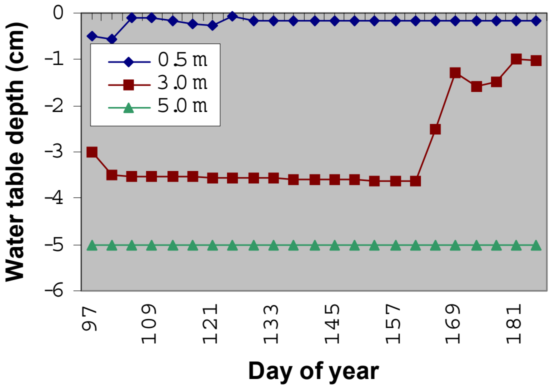

Figure 1. Fluctuations of water table depth during the growing season for three initial water table depths (day 97=April 7 and day 185= July 4).

Effect of irrigation and drainage

Simulated 10-year mean grain yields for mungbean planted early (15 March), medium (7 April) and late (30 April) for varying water table, drainage, and water regime are presented in Table 1. The Table also records 10-year mean values for soil water deficit and relative aeration stress indices.

When sub-surface drainage was provided, overall grain yields were greater under irrigation (1.26 to 1.69 t ha^{-1}) than rainfed (0.40 to 1.68 t ha^{-1}) irrespective of water table depth and planting date. In contrast, without drainage, yields varied according to the depth of the water table. Under the SWT, yields were greater for rainfed (0.43 to 0.94 t ha^{-1} vs. 0.43 to 0.85 t ha^{-1}) but under the DWT, they were greater for irrigation (0.92 to 1.31 t ha^{-1} vs. 0.40 to 0.92 t ha^{-1}).

The irrigated crops experienced little soil water deficit (index greater than 0.93) in contrast to rainfed crops (index between 0.60 to 0.98) irrespective of whether drainage was provided or not. With drainage, both irrigated and rainfed crops experienced little aeration stress (index greater than 0.85), but without drainage, the crops were waterlogged and experienced substantial aeration stress. The stress was slightly greater for irrigated crops (index between 0.51 to 0.87) than for rainfed ones (index between 0.59 to 0.9), and waterlogging was more severe under SWT (indices of 0.51 to 0.90) than DWT (indices of 0.70 to 0.94).

Effect of planting date

With irrigation, mean grain yields did not differ significantly for various planting dates when drainage was provided and were greater for SWT (1.60 to 1.69 t ha^{-1}) compared to DWT (1.26 to 1.36 t ha^{-1}). The CPDFs, however, showed that in about 70% of the years, yields were greater for late compared to early planting under the SWT, while under the DWT, they were greater in only 50% of the years (Figure 2). Without drainage, however, yields were significantly greater for early than late planting irrespective of the water table depth. The respective yields were 0.85 and 0.43 and 0.92 and 1.31 t ha^{-1} respectively for SWT and DWT (Figure 3).

The associated CPDFs for SWDF and aeration stress indices for various planting dates revealed that greater yields for late planting for either water table depth were due to reduced water deficit. With drainage, the late-planted crop experienced little aeration stress under DWT but substantial stress under SWT (Figure 2). In contrast, the crop under SWT experienced slightly more water deficit, but little aeration stress when planted early (either on 15 March or 7 April). The CPDFs for simulated yields were completely different for undrained fields with irrigation (Figure 3). Under the SWT, the overall yields across the planting dates over 10 years ranged from 0.1 to 1.3 t ha^{-1} while under DWT, they ranged from 0.3 to 1.6 t ha^{-1} and were greatest for early planting and smallest for late planting. Under the SWT, yields ranged from 0.5 to 1.3 t ha^{-1} for early planting and were greater than 0.8 t ha^{-1} in 50% of the years. For late planting, however, the yields ranged from 0.1 to 0.8 t ha^{-1}, with yields greater than 0.5 t ha^{-1} in only 40% years. Under DWT, yields for

Table 1. Simulated mean grain yields (kg ha^{-1}), and soil water deficit (SWDF) and aeration stress (AF) indices as affected by planting date (early, medium, late), water table depth (SWT, DWT), drainage, and irrigation*.

	Yield			SWDF			AF		
	Early	**Medium**	**Late**	**Early**	**Medium**	**Late**	**Early**	**Medium**	**Late**
				Irrigated					
Drained									
SWT	1640	1597	1689	0.93	0.93	0.97	0.99	0.99	0.85
DWT	1358	1255	1326	0.93	0.93	0.97	0.89	0.87	0.99
Non-drained									
SWT	847	564	425	0.93	0.94	0.98	0.73	0.62	0.51
DWT	1312	1071	922	0.93	0.93	0.97	0.87	0.80	0.70
				Rainfed					
Drained									
SWT	699	1112	1679	0.67	0.81	0.97	1	0.98	0.98
DWT	404	765	1342	0.6	0.79	0.97	0.95	0.91	0.85
Non-drained									
SWT	746	939	425	0.71	0.9	0.98	0.9	0.79	0.51
DWT	399	791	920	0.6	0.78	0.97	0.94	0.91	0.71

* mean of 10 years. SWT=shallow water table, DWT=deep water table.

early planting ranged from 0.7 to 1.6 t ha^{-1}, and exceeded 1.2 t ha^{-1} in 80% of the years, while for late planting the yields ranged from 0.3 to 1.4 t ha^{-1}, with greater than 1.2 t ha^{-1} only in 20% of years.

Though the crop did not experience water stress under either water table depth when planted late, it experienced significant aeration stress (Figures 2 and 3). Conversely, when planted early, the crop experienced less aeration as well as less water deficit stress. Since the crop was irrigated and the field was not drained, there was no water deficit stress for either planting date or water table regime. Thus the greater yields for early planting were mainly attributed to less aeration stress compared to other two planting dates.

Effect of watertable

Figure 4 shows the CPDFs for simulated irrigated grain yields for drained and undrained fields with varying watertables for the 7 April planting date. The yields over 10 years for drained fields ranged from 1.0 to 1.8 t ha^{-1} while those for undrained, ranged from 0.4 to 1.7 t ha^{-1}. When the field was drained, crops under SWT experienced little water stress and no aeration stress in any year. Without drainage, however, it experienced significant aeration stress (indices of 0.4 to 0.7 in 90% of years).

In undrained fields, maximum yield was 1.2 t ha^{-1} for SWT and 1.7 t ha^{-1} for DWT. When water came intermittently close to the surface some waterlogging severely limited yields. The crops under the DWT, however, produced greater yields due to fewer waterlogging events, seen by less aeration stress (aeration indices of 0.7 to 0.9 in 80% of years). Water deficit stress was not pronounced under either watertable regime although in about 40% of years the crop under the SWT experienced slightly less stress than under the two deeper watertables (Figure 4).

For drained fields under rainfed conditions, CPDFs indicated that in 90% of the years, yields were greater under the SWT than the two deeper water tables. In about 50% of years, yields under SWT were greater than 1 t ha^{-1}, but under the deeper water tables, they exceeded this in only about 30% of years. In all the years, crops experienced less water and aeration stress under SWT than DWT (Figure 5). Under undrained rainfed conditions, the yields ranged from 0.1 to 1.7 t ha^{-1}, with consistently greater yields for SWT compared to the deeper water tables (Figure 5). Since the field was undrained, there was less water stress under the SWT than the deeper water tables. However, the crop under SWT experienced greater aeration stress due to the absence of sub-surface shallow drainage than under the deeper water tables.

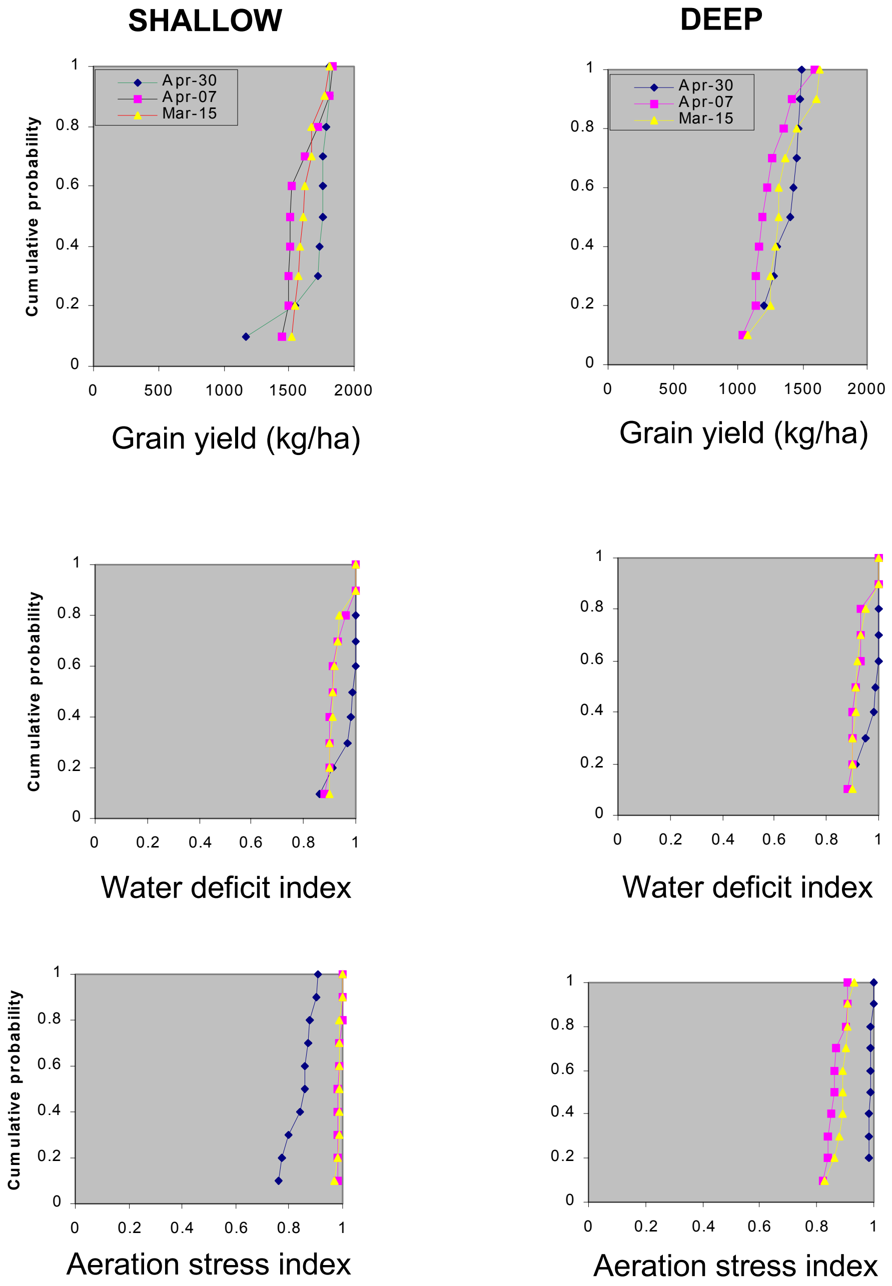

Figure 2. Effect of planting date of mungbean on the cumulative probability distribution functions for grain yield, and water and aeration stress indices under drained shallow and deep water tables.

DISCUSSION AND CONCLUSIONS

Under current farming practice, farmers generally do not irrigate pre-rice mungbean crops and do not have drainage facilities. Under such conditions, the average yield is 0.5 t ha^{-1} and there are risks of crop failure due to water deficit as well as waterlogging. If planted early, there is a risk of water deficit but if planted late, there is a risk of waterlogging. However, if shallow drainage could be provided, the model reveals that late planting would be the best strategy under the rainfed condition because crops would avoid water deficit during the vegetative period and waterlogging during the reproductive stages (Table 1).

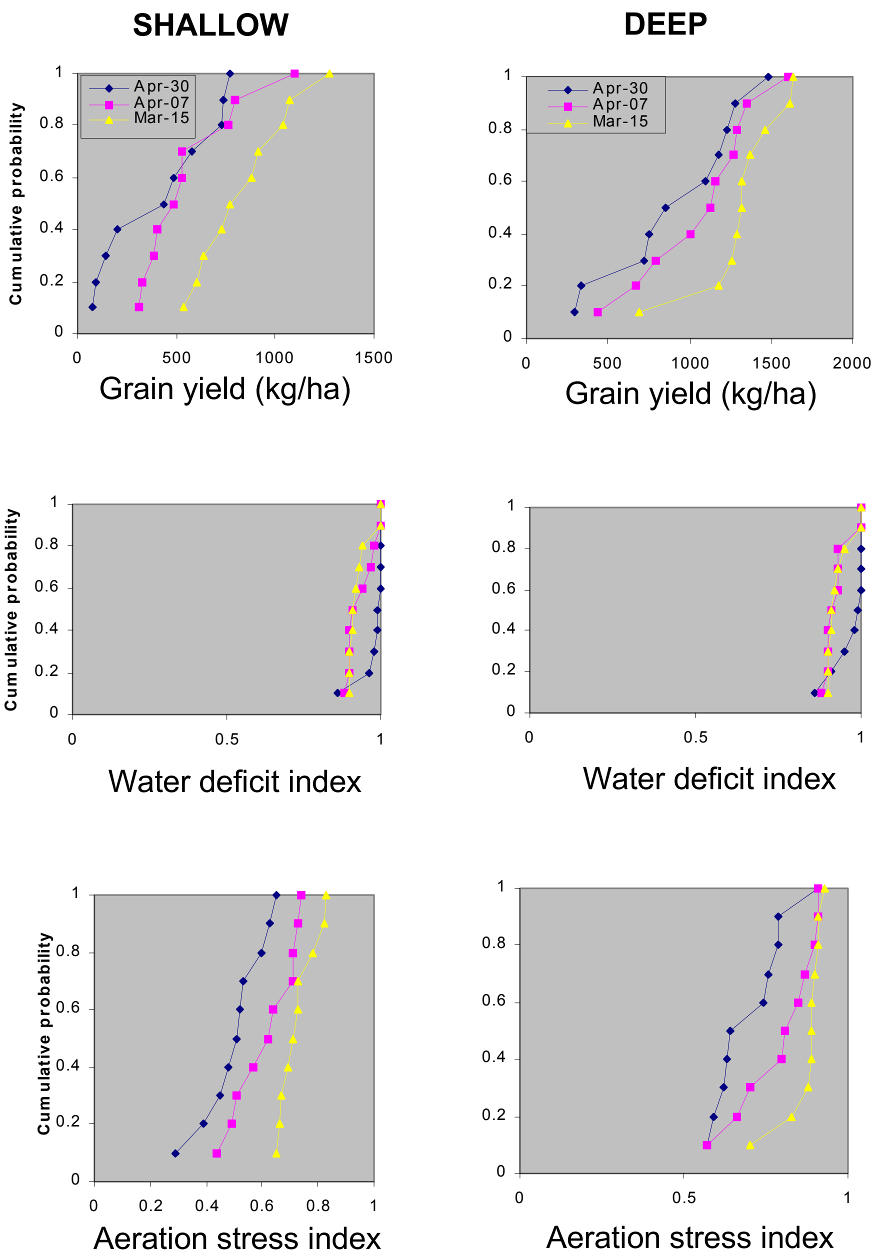

Figure 3. Effect of planting date of mungbean on the cumulative probability distribution functions for grain yield, and water and aeration stress index under non-drained shallow and deep water tables.

With irrigation facilities, however, early planting would be the best strategy especially when shallow drainage could not be provided. Under such conditions, the crop would not suffer from water deficit and would only suffer from moderate waterlogging. However, if planted late, yields under the SWT could be reduced by up to 50% because the crop would suffer from both waterlogging and aeration stresses. In DWT also, there would be yield reduction by up to 25-30%. With both irrigation and drainage facilities, however, late planting would still be the better strategy despite year to year variability in yield (Figures 2 and 3).

Finally, under both rainfed and irrigated conditions, late planting would be the better strategy if shallow sub-surface drainage could be provided. In contrast, if drainage could not be provided, early planting would be better under irrigation while late planting would still be better under rainfed condition. Nevertheless, since mungbeans have to mature

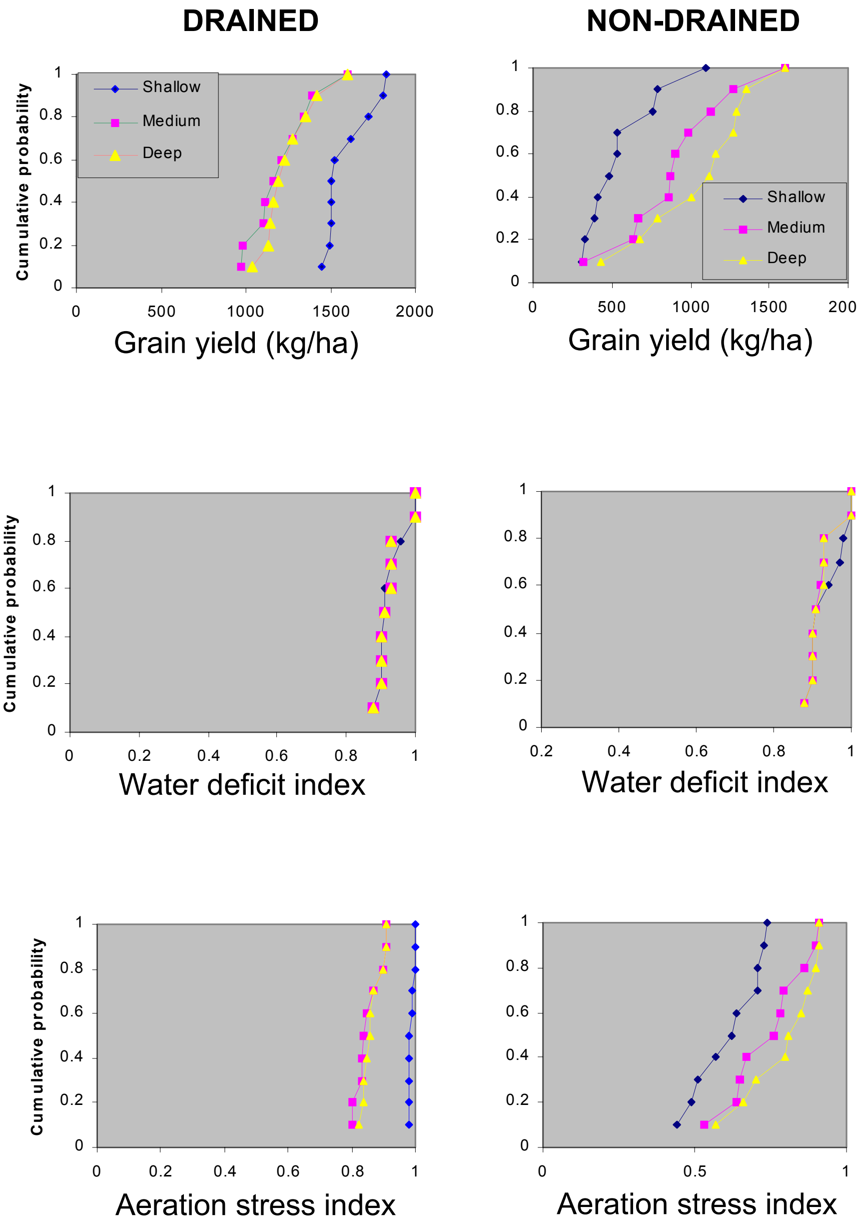

Figure 4. Effect of water table depth on cumulative probability distribution functions for grain yield, and water and aeration stress indices, planted on 7 April under irrigation with and without drainage.

early to fit into rice-wheat systems, early planting would always be the best strategy, however, it would require some drainage facilities.

The simulation results presented here reflect the preliminary attempts to demonstrate the potential use of SWAGMAN Destiny model for addressing water management related issues in Bangladesh. The model, however, requires extensive testing under a range of environments before it can be applied to investigate various scenarios and extrapolate the results to other environments.

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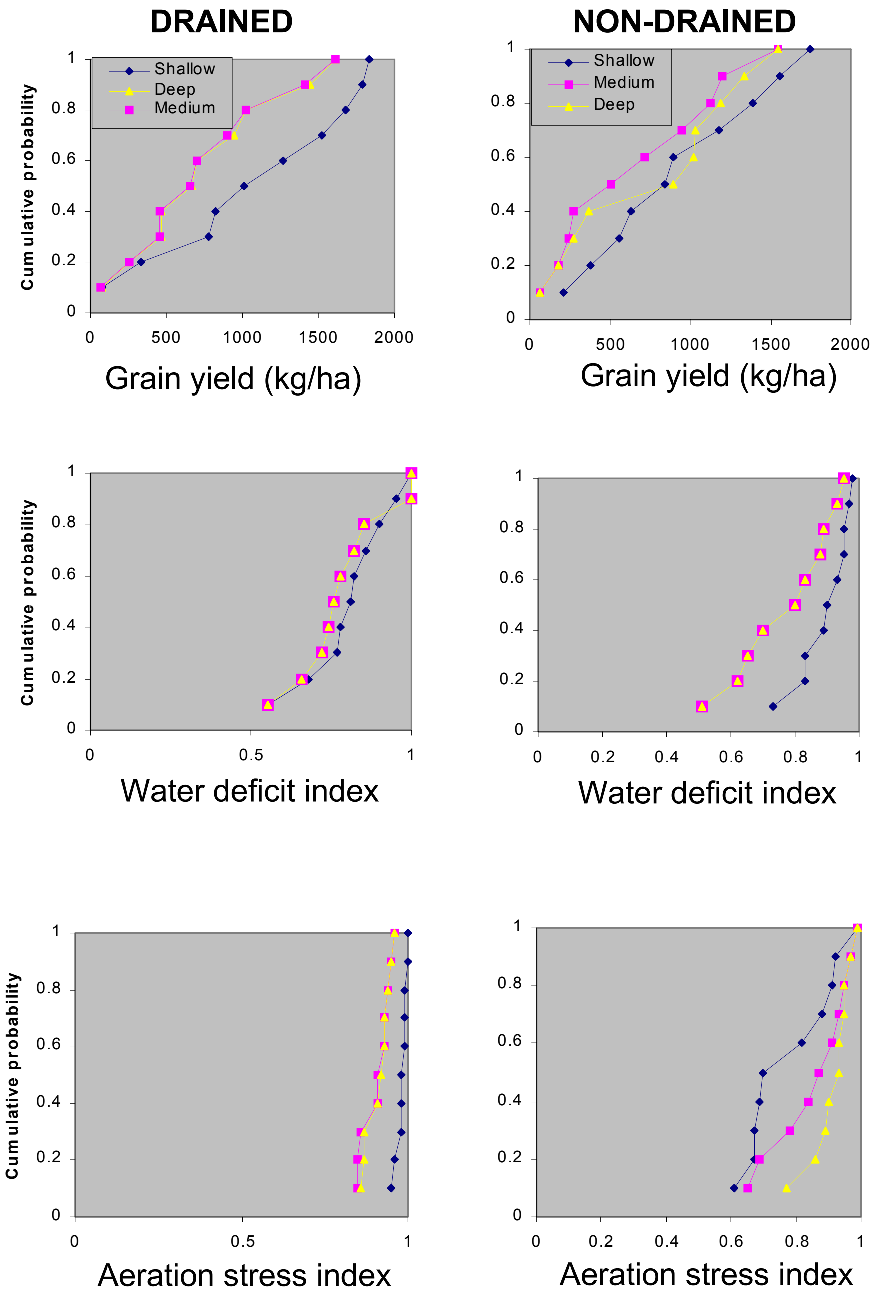

Figure 5. Effect of water table depth on cumulative probability distribution functions for grain yield, and water and aeration stress index, planted on 7 April under rainfed with and without drainage.

Water, Adelaide provided air fare for the first author to travel to Peru to attend the symposium.

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