Modelling irrigated cropping systems, with special attention to rice-wheat sequences and raised bed planting

Proceedings of a workshop at CSIRO Land and Water, Griffith
25-28 February 2002

Editors: E. Humphreys and J. Timsina

Australian Centre for International Agricultural Research

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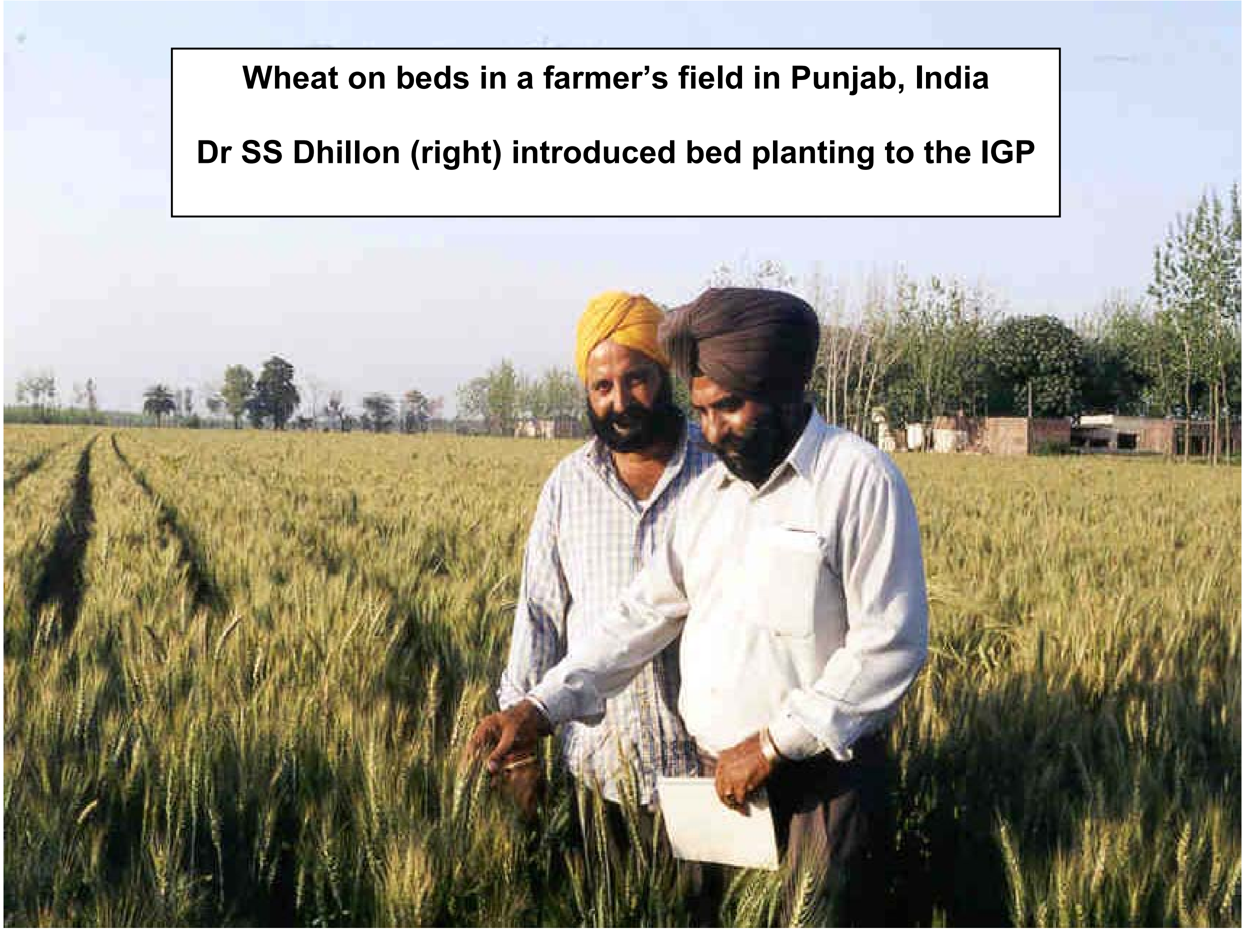
CSIRO Land and Water Technical Report 25/02



Wheat on beds in a farmer's field in Punjab, India

Dr SS Dhillon (right) introduced bed planting to the IGP

Direct-seeded rice on beds in a farmer's field in Australia

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Foreword

The rice-wheat cropping systems of the Indo-Gangetic Plains (IGP) are of immense importance for food security for south Asia. Over the past 40 years the increase in rice and wheat production has kept pace with population growth due to improved varieties, increased inputs, especially fertilisers, and the expansion of irrigation. However yield stagnation, and possibly yield decline, water scarcity, and water and air pollution are major threats to the sustainability of rice-wheat systems and food security. Therefore the design and implementation of alternative production systems with increased resource use efficiency (especially water) and productivity and reduced adverse environmental impact are urgently required.

Bed farming, practised for several decades for crops other than rice in Australia, Mexico and elsewhere, was introduced to the rice-wheat regions of the IGP in the mid 1990s. Farmer experience and research have shown that bed farming offers significant advantages for productivity and resource use efficiency for wheat and other non-rice crops. More recently, attention has focused on the possibility of also growing rice on beds in the IGP and Australia, with the associated potential benefits of permanent bed systems including reduced land preparation costs and turn around times, increased cropping flexibility, and increased productivity of “upland” crops grown in rotation with rice due to improved drainage and soil structure and improved rotations.

The radical shift from ponded rice culture on the flat (with or without puddling and transplanting) to intermittently flooded bed layouts affects a host of interacting factors influencing productivity and resource use efficiency of both rice and crops grown in rotation with rice. These factors range from weeds to nutrient availability to pests and diseases to water dynamics to stubble management options. The potential benefits and disadvantages of permanent bed systems need to be quantified under a range of agroecological conditions, and optimum layouts and management systems need to be identified to maximise potential gains.

The Australian Centre for International Agricultural Research (ACIAR) is funding a major new project LWR2/2000/89 *Permanent beds for rice-wheat and alternative cropping systems in north west India and south east Australia.* This is a collaborative project between Punjab Agricultural University, CSIRO Land and Water and NSW Agriculture, with additional support from the International Atomic Energy Agency (IAEA/FAO) for the work in India, and additional support for the work in Australia from the Rural Industries Research and Development Corporation (RIRDC) Rice program, the Grains Research and Development Corporation (GRDC) and Coleambally Irrigation Cooperative Ltd and Murray Irrigation Ltd.

The major part of the project comprises field comparison of permanent bed and traditional layouts for rice-based cropping systems in Punjab, India and NSW, Australia, with detailed monitoring, in particular focusing on crop growth and development, water and nitrogen dynamics and balances, and options for stubble management. The project also seeks to further develop and refine models for rice-wheat and alternative systems, and apply them to evaluate permanent bed and traditional layouts for a range of agroecological environments, and to identify options for maximizing resource use efficiency and productivity of rice-wheat cropping systems in India, and rice-based cropping systems in Australia. Therefore an early activity in the project was a workshop bringing together a small group of international scientists leading in the development and application of crop models including the modelling of crop sequences and two-dimensional approaches.

The objectives of the workshop were:

1. to review the state of the art in the modelling irrigated cropping systems (crop sequences as opposed to single crops) and bed geometries (as opposed to "flat" layouts)

2. to workshop conceptualizations of the ways forward in modelling crop sequences and bed layouts, and with particular attention to rice-wheat systems

3. to establish a network of contacts working in these areas to share progress and problems in the future

Acknowledgements

We are grateful to all workshop participants and their organisations for their participation, recognizing the significant time and monetary costs involved.

Sponsorship of international participants was provided by ACIAR, APSRU (Agricultural Production Systems Research Unit), the Crawford Fund and IRRI (International Rice Research Institute).

We thank Professor David Connor, University of Melbourne, for ably facilitating the workshop.

Liz Humphreys
Workshop Convenor

Contents

Key questions, issues and opportunities, and recommendations

Some issues on water and nitrogen dynamics in rice-wheat sequences on flats and beds in the Indo-Gangetic plains

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Rice-wheat systems of the Indo-Gangetic plains

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) grown sequentially in an annual rotation constitute a rice-wheat system. The system brings together conflicting and complementary practices as repeated transitions from aerobic to anaerobic to aerobic soil conditions change the physical, chemical and biological environment of soils, and most importantly, soil structure and nutrient relations (Timsina and Connor 2001). In the annual cycle, suitable thermal conditions for both rice and wheat exist in the Indo-Gangetic Plains (IGP) (Figure 1), where climate is sub-humid with a distinct wet, monsoon, summer season and a dry, cool, winter season. Temperatures can exceed 45°C in summer and frost occurs in some areas in winter. Soils are mainly alluvial, based on deposits of the Indus and Ganges river systems. Texture ranges from loamy sand to silty clay loam. Many soils are alkaline, although acid soils are also present in the piedmont and some floodplains. The northwest part of the IGP is endowed with extensive canal irrigation systems using water storage reservoirs in the Himalayan mid-hills. Canal irrigation is supplemented with tube-well water and most of the rice-wheat areas are either fully or partially irrigated. The IGP is probably one of the most fertile and productive agricultural areas in the world.

The rice-wheat rotation is one of the world's largest agricultural production systems (13.5 M ha in South Asia), occupying about 85% of the cultivated land in the IGP and nearly one-sixth of the total geographical area of the sub-continent. The system accounts for about one-third of the area of both rice and wheat grown in South Asia. Rice-wheat rotations produce more than 45% of the region's food, and provide staple grains for nearly 42% of the total population of 1.3 billion of South Asia. Demand for rice and wheat in south Asia will grow at 2.5% per year over the next 20 years, but the per capita rice-wheat growing area has already shrunk from 1,200 m^2 in 1961 to less than 700 m^2 in 2001. Future growth in food production can only come from increased yield rather than area (Ladha et al. 2000).

The IGP has been subdivided into four transects encompassing five broad regions -- the Trans (region 1 in Pakistan and 2 in the Indian Punjab and Haryana); Upper (region 3, with most of Uttar Pradesh and parts of Bihar and Nepal); Middle (region 4, with most of Bihar and parts of Nepal); and Lower (region 4 in eastern India, and region 5 in Bangladesh) IGP (Fig. 1). Solar radiation decreases from IGP transect 1 to 5 in the rice season whilst the trend is reversed in the

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wheat season. Minimum temperature in rice and wheat increases as you move from IGP Transects 1 to 5. This is also true for maximum temperature in the wheat season but during the rice season, the average maximum temperature is similar across all of the IGP. Rainfall also follows a distinct pattern, increasing from Transects 1 to 5 of the IGP, with Transects 1 and 2 receiving only 650 mm of rainfall per annum and Transect 5 receiving over twice as much. Except for rainfall, the climatic conditions, make the upper transects of the IGP more favourable for rice and wheat cultivation. Access to assured irrigation has alleviated the problem of low rainfall periods and made the zone (Transect 1 and 2) very productive. Less favourable climatic conditions and limited irrigation facilities are the major constraints to higher yields in the lower transects (Transects 3, 4 and 5) of the IGP. In the Trans- and western parts of the Upper-Gangetic Plains, the rice-wheat system mostly includes indica-type monsoon rice and spring wheat, because there is generally insufficient time for a third crop. In the eastern part of the Upper-Gangetic Plains, and in the Middle- and Lower-Gangetic Plains the rice-wheat systems often include a third crop (such as mungbean, cowpea, jute) after wheat/before rice.

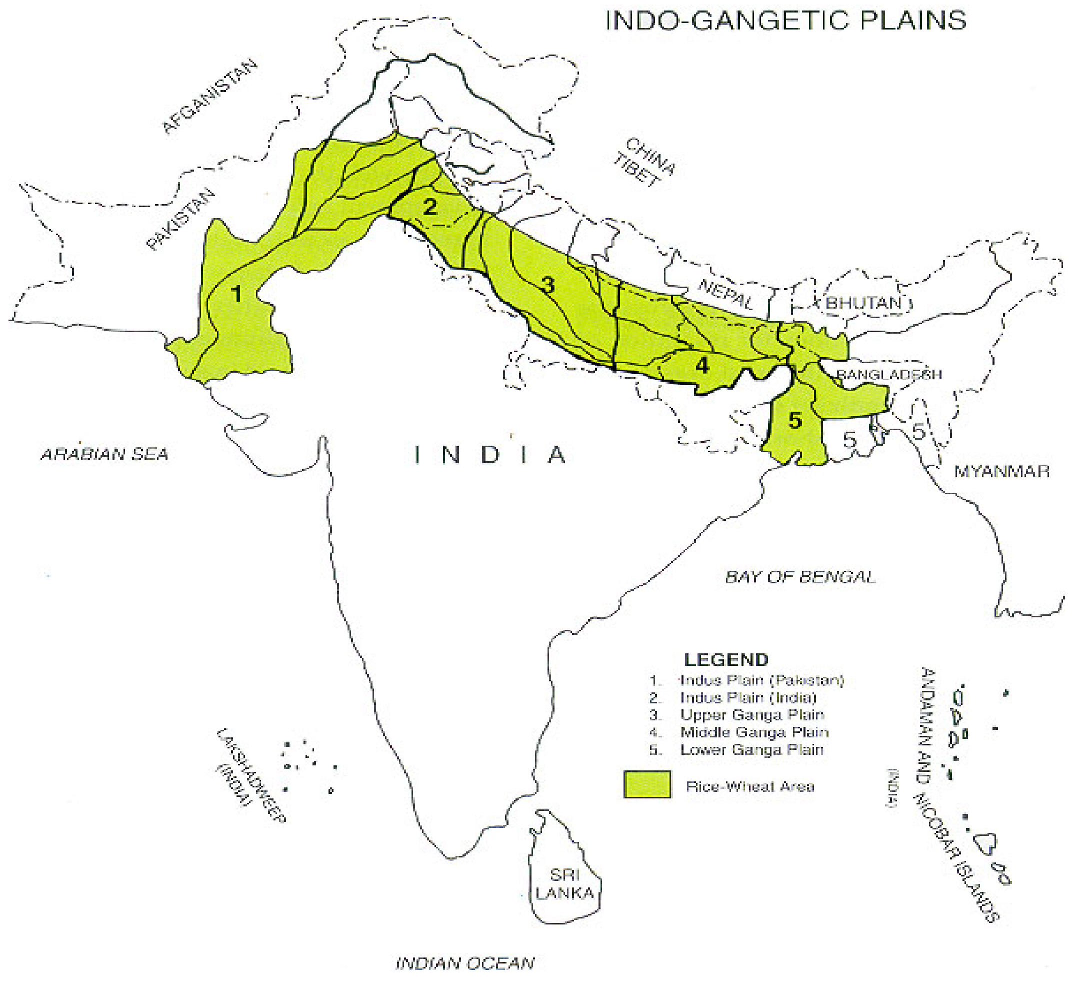

Figure 1. The rice-wheat areas of the Indo-Gangetic Plains by transect (modified from Huke and Huke 1992)

The yields of both rice and wheat have gradually increased over the past four decades as the rice-wheat system has developed. Rice yields more than wheat but mean yields of both crops in the four South Asian countries (2.7 and 2.1 t ha^{-1} for rice and wheat, respectively) are small relative to potential attainable yield. Much of the system, especially in the middle and lower IGP, operates at low yield because of inadequate nutrition and poor water management. In the Trans- and Upper IGP, however, mean yields of both crops are substantially higher, because of assured irrigation and high nutrient use. The challenge to research is to understand crop responses to the required combination of practices so that management systems can be devised for high and sustainable system yield (Timsina and Connor 2001).

Rice-wheat systems of the Indian Punjab

Punjab and Haryana are the home of the 'Green Revolution' in India, where the use of seed of high yielding, short duration and N responsive cultivars, extensive use of chemical fertilizers and pesticides, irrigation, and improved farm machinery have been implemented starting from the 1960s. Hot, wet summers and cold dry winters characterize the climate of Punjab. The annual rainfall in Punjab ranges between 400-800 mm, increasing from west to east, and is equivalent to around 40% of potential evapo-transpiration (Fig. 2). The soils of the region are predominantly coarse textured (sands, loamy sands, sandy loams and loams) with smaller areas of silty clays and clays. The traditional rice fields have loam to clay loam soils, but the non-traditional rice soils, which came under cultivation to rice from the mid-70s, are more porous (sands, loamy sands, and sandy loams), and now constitute about 60% of rice soils of Punjab. Punjab is now the greatest user of irrigation water and fertilizer for rice and wheat in India.

Rice replaced traditional crops of maize, sorghum, pearl millet, cotton, and pulses, while wheat replaced barley, pulses, and mustard. The central plain districts of Punjab show the maximum concentration of rice because this zone has the highest irrigation intensity in the country, with more than 94% of the net area sown being irrigated through a network of perennial canals and nearly 0.8 million tube-wells. Thus in Punjab the rice area has increased from 0.4 M ha in 1960-61 to 2.8 M ha in 1990-91, while the wheat area increased from 1.7 to 3.2 M ha over the same period (Yadav et al 1998). The shift in cropping patterns was also associated with increased yields of rice from 1.0 t ha^{-1} to 5.1 t ha^{-1} between 1960-61 and 1996-97, and of wheat from 1.0-2.0 t ha^{-1} to 4.2 t ha^{-1}. Now the groundwater reserves are being over exploited, with sharp declines in ground watertables, averaging 20 cm per annum. Although sustainability of rice cultivation is at risk due to falling watertables (at some places 100 cm per annum), an increase in rice area has continued because stable yields of rice are being obtained with high use of N fertilizers (120-150 kg N ha^{-1}), assured irrigation, and favorable growing conditions (13-14 h bright sunshine per day during most of the growth period of rice). On relatively coarse-textured soils, farmers apply about 1500 mm of irrigation water over a 100-110 day growing period to supplement the 330 mm average effective rain received during the season.

The total productivity of rice and wheat in Punjab is the highest (5.1 + 4.2 = 9.3 t ha^{-1}) in the country (Statistical Abstract of Punjab, Economic Advisor, Punjab, Chandigarh). There are concerns over the sustainability of the rice-wheat system in Punjab and this system is no longer exhibiting increased production with increases in input use. It is suggested that by incorporating suitable innovations the system will overcome the emerging problems of receding watertables and depleting soil fertility (Narang and Virmani 2001). Immediate research priorities seem to be the development of water saving technologies matched with efficient use of nutrients by rice and wheat, and the development of methods to recycle the large amounts of rice and wheat residues that are burnt, wasting nutrients and causing environmental pollution.

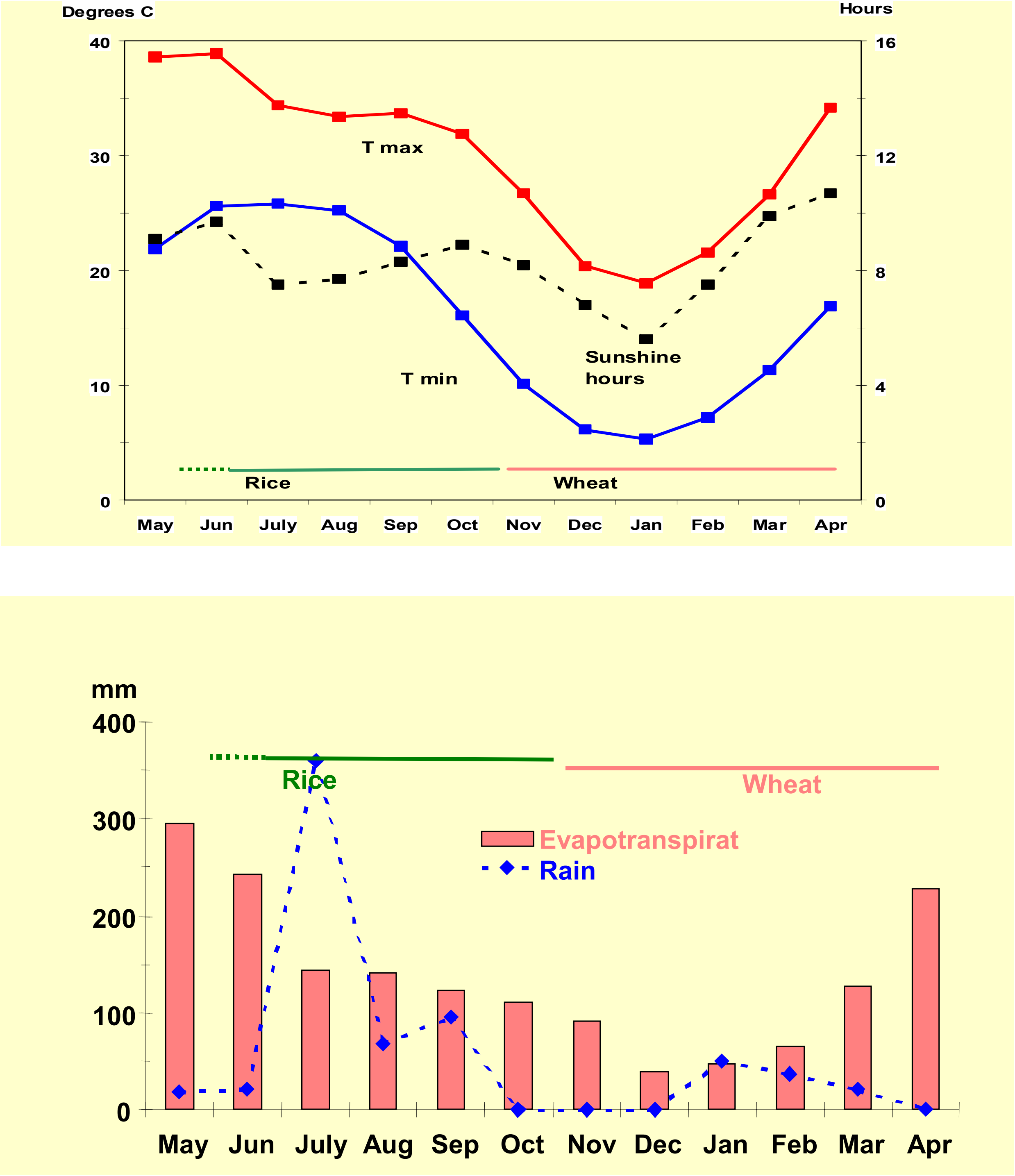

Figure 2. Monthly mean climatic data at Ludhiana, Punjab

Nitrogen management in rice-wheat systems

Fertilizer use in rice and wheat in India

The productivity of both rice and wheat is related to total use of N, P and K. Diagnostic surveys (Yadav et al. 2000) indicate that farmers apply 130-195 kg N ha^{-1} to non-basmati rice, with an average of 153 kg N ha^{-1} in Punjab. The ability to irrigate substantially influences the use of fertilizer N and the productivity of both rice and wheat crops. A positive interaction between water and nutrient use in the rice-wheat system is well documented.

Transformations and losses of nitrogen

Nitrogen from rice-wheat systems is mostly lost via ammonia volatilization, nitrification-denitrification, and leaching.

Nitrification
In several areas in the IGP, continuous flooding for rice usually cannot be maintained either due to shortage of water or due to high percolation rates, leading to alternating flooded (reduced or anaerobic) and drained (oxidized or aerobic) conditions. Consequently, nitrification occurs during "dry spells" and nitrates thus produced are subsequently reduced to N_2 and N_2O by denitrification when soils are reflooded. Although there is much variation in the data on nitrification rates estimated at different locations in the IGP, a trend with respect to soil temperature and pH is easily discernible (Aulakh and Bijay-Singh 1997).

Nitrification rates in excess of NO_3^- utilization by plants can result in increased levels of NO_3^--N in run-off and groundwater rendering it unsafe for human consumption. On the other hand, slow rates of nitrification would result in accumulation of NH_4^+-N, which may enhance fertilizer-use efficiency by reducing denitrification and leaching losses. However, reduced nitrification could also increase N losses via NH_3 volatilization. Thus nitrification acts as a key process in determining fertilizer-use efficiency by crops as well as N losses from soils. Since the major portion of total fertilizer N used in the rice-wheat cropping systems in the IGP is urea, the rate of nitrification is a primary determinant of N losses. The use of neem (*Azadirachtca indica*) cake or neem extract coated urea has been shown to retard nitrification in soils and enhance N use efficiency in rice under many situations.

Ammonia volatilization
In coarse-textured or porous soils grown to rice, NH_4^+-N in floodwater is readily transported to subsurface soil layers along with percolating water, and cannot move back to the soil surface due to the downward flux of percolating water. Thus, in contrast to heavy clay soils, highly permeable soils under wetland rice are not prone to substantial losses of N via ammonia volatilization. Urea is generally applied after the first irrigation to minimize leaching and denitrification losses, but its placement on the wet surface of alkaline porous soils promotes ammonia volatilization. Since leaching and denitrification are not significant loss mechanisms in wheat crops, volatilization of NH_3 seems to be the most likely mechanism of loss (Katyal et al. 1987). The timing and placement of fertilizer and the timing of irrigation could further influence the losses of urea applied to porous soils. When applied on the wet soil surface following irrigation, as much as 42% of the applied N was lost, most likely due to volatilization. Deep

placement of urea before irrigation reduced the loss of applied N from 42 to 15% (Katyal et al. 1987).

Denitrification

In submerged soils under rice, nitrification in oxidized soil zones and floodwater converts the ammonical N formed by ammonification and hydrolysis of urea into nitrate N. The nitrate N can then move into reduced soil zones where it is readily denitrified. Thus alternating aerobic–anaerobic conditions in soils under rice could result in greater total N loss from the soil than would be found under continuous anaerobic conditions. Very limited information is available, however, of the direct measurement of gaseous N losses via denitrification. A recent study carried out by Aulakh et al. (2001) estimates that 23-33 % of N applied through fertilizer and/or green manures is lost via nitrification-denitrification during rice cropping. In wheat, losses could be 8-10 fold less than in rice.

Leaching

In ideal lowland rice fields with fine-textured soils, nitrification proceeds very slowly producing small amounts of nitrates, and due to restricted downward percolation, with little loss by leaching beyond the rice root zone. In coarse-textured soils, however, leaching losses of NO_3^- and also unhydrolyzed urea may occur, particularly if applied as large granules. In wheat, losses of applied N are not large. For urea-based sources, about 75% of the applied N was found in the top 15 cm soil, reflecting little or no leaching of N (Katyal et al. 1987). When applied before irrigation, however, N derived from urea moved down to 15 to 30 cm. In rice, N losses via leaching were determined by the percolation rates as modified by puddling and the N source. Applying N to rice through urea supergranules (USG) in porous soils resulted in negligible losses via ammonia volatilization but extremely small fertilizer use efficiency due to large losses via leaching (Katyal et al. 1985).

Bijay-Singh and Sekhon (1976) reported that the concentration of NO_3^- in the water from shallow (4 to 10 m deep) open wells located in cultivated areas decreased significantly with depth to watertable, and was positively correlated with the amount of fertilizer N applied on farms located in the vicinity of the wells. During 1975 to 1988, average fertilizer N consumption in the Indian Punjab increased from 56 to 188 kg N ha^{-1} year^{-1} (on net area sown basis). Monitoring of the NO_3-N concentrations in the shallow well waters in 1982 and 1988 (Bijay-Singh et al. 1991) revealed that the increase of NO_3^--N by almost 2 mg l^{-1} was associated with an increase in fertilizer consumption. In a recent survey conducted in 1999, NO_3^--N content in shallow groundwaters drawn though some hand pumps located in village peripheries was more than 10 mg l^{-1}. Even in tube wells located at farms in the Punjab, NO_3^--N level in water has increased from 0.4 mg l^{-1} in 1975 to 3.6 mg in 1992 to >5 mg l^{-1} in 1999.

Amounts, sources and placement of N application

Irrespective of source, application of fertilizer N at 120 kg ha^{-1} is recommended for most of the rice-wheat growing regions, except in the eastern parts of the IGP, where lower N rates are applied. In soils with low organic carbon, significant and economic responses of rice and wheat have been recorded for application rates up to 150 kg N ha^{-1}. The trend is already evident with more than 150 kg N ha^{-1} applied to rice following wheat in Indian Punjab, Haryana and Western

Uttar Pradesh, and where grain yield of 10 to 12 t ha^{-1} per annum are being obtained for the rice-wheat system (Yadvinder-Singh and Bijay-Singh 2001).

Though urea is the main source of fertilizer N for the rice-wheat system in the Indo-Gangetic plains of South Asia, small quantities of calcium ammonium nitrate (CAN), ammonium chloride and ammonium sulphate are also available to farmers. Nitrate containing fertilizers such as CAN when applied to rice have proved to be less efficient because nitrate is prone to loss via denitrification and leaching under submerged soil conditions.

It has been observed that, depending upon soil and agroclimatic conditions, a single deep-placed application of USG gave an average yield benefit of 15-20% over that obtained by the same amount of N applied in split doses through prilled urea. Deep placed USG, however, did not perform better than prilled urea in coarse textured soils with high percolation rates in Indian Punjab. In spite of the distinct advantage of USG in fine textured soils, it has not gained popularity among farmers due to the lack of suitable mechanical applicators (Yadvinder-Singh and Bijay-Singh 2001).

Time and method of N application

Fertilizer N applied at a time when crop needs are high reduces the chances of losses of N from the soil-plant system, leading to better N-use efficiency. Application of fertilizer N in three equal splits to rice at transplanting, tillering (21 days after transplanting [DAT]) and panicle initiation (42 DAT) provides a greater grain yield response than one or two doses, irrespective of source of N and type of soil. Application of N at 7 DAT proved more beneficial than application at transplanting, because the crop requirement of N during the first seven days is likely to be very small (Meelu et al. 1987).

Application of fertilizer N in two equal splits, half at sowing and half at crown root initiation (along with the first irrigation), has been found beneficial in increasing grain yield and N uptake of wheat, and it is a general recommendation over a vast area under wheat in the IGP. Moreover, application of the first half N dose with pre-sowing irrigation resulted in significantly higher wheat yield than at sowing. Possibly N applied along with pre sowing irrigation was transported to depth and thus was not prone to losses of N via ammonia volatilization. Recent studies have shown that need-based N management in rice using the leaf colour chart helped in reducing fertilizer N use by 25% and thus minimized N losses and lessened the risk of NO_3 pollution of ground water.

Tillage management in rice-wheat systems

In the IGP, tillage for rice comprises of series of dry (pre-puddling) operations after wheat harvest followed by wet tillage and puddling in ponded water prior to rice transplanting. Pre-puddling tillage is done to chop and mix residues, incorporate amendments and manures, check weeds and facilitate water soaking. While pre-puddling tillage is generally done with a disc harrow and/or tyne harrow, puddling is generally done with a tyne harrow followed by leveling by a wooden bar (planking). Puddling, an energy intensive process, is performed to counter water, nutrient, and weed related constraints. In addition to benefits such as ease of transplanting, better root proliferation and increased nutrient-use efficiency, farmers' perceptions of puddling as a composite part of rice culture are mainly centered around its role in suppression of weeds and reduction of water losses. More than 60% of the rice area in the IGP receives 2-3 pre-puddling, 2 puddling, and 2 planking operations. In some areas with less water available for irrigation, farmers perform 4 to 5 puddlings. Puddling, destroys soil aggregates, increases bulk density below the puddled layer, decreasing the proportion of transmission pores and hydraulic conductivity, and therefore decreases the percolation rates. Destruction of aggregates and increase in bulk density may influence the performance of crops following rice, however the evidence for this is inconsistent and inconclusive (Gajri et al.1992; Connor et al. 2002). An important question is whether there are gains to be made by moving away from puddling to better meet the edaphic requirements of both rice and wheat.

Likewise, much labor and energy are spent in seedbed preparation for wheat. Tillage consists of 3 operations: (i) disc harrowing as primary tillage, (ii) tyne harrowing as secondary tillage and (iii) planking to level the land. These operations are performed after burning of rice residues after harvest. It is followed by irrigation, tyne harrowing and planking at the time of seed bed preparation. In some areas, where the period before wheat seeding is short and there is enough moisture for germination of wheat, the pre-seeding irrigation is omitted. In general, more than 80% of the wheat area in the IGP is tilled (disc or tyne harrowed) more than 4 times followed by 2-3 plankings. Recently, however, many farmers, especially in Haryana and in the eastern IGP under fine-textured soils, have started seeding wheat with no or reduced tillage, with or without burning of rice residue. Research efforts are underway to replace the conventional tillage systems for wheat with zero or reduced tillage, bed farming, surface seeding, etc. in soils or regions appropriate for these methods. Residue retention or incorporation will have to be an integral component of any future tillage system evolved for the rice-wheat system.

Residue management in rice-wheat systems

Throughout the IGP there is little retention of crop residues in the field – they are either harvested for fuel, animal feed or bedding, or are burnt in field. Combine harvesting of rice and wheat is now becoming popular among farmers in western parts of the IGP, which leaves a huge amount of rice residues in the field. It leaves behind both anchored (40-50 cm high) and loose crop residues in windrows, which can hinder planting of the following crop. In the Indian Punjab and Haryana provinces, about 90% and 45% of area under rice are harvested by machine, respectively, and rice residue is either completely burnt after use of a shredder, or partially (~45%) burnt (P.R. Gajri , unpublished data, 2002). Under wheat, the machine-harvested area is 82% in Punjab, 30% in Haryana, 55% in Tarai UP, and 31% in eastern UP. In the machine-harvested wheat fields a chaff maker is used to collect the chaff for fodder leaving only about 15-20% residue in the field, which is usually disposed of by burning. These estimates show that 10.7 Mt of rice residues is burnt in Punjab, 2.7 Mt in Haryana, 0.7 Mt in Uttranchal and 2.1 Mt in Eastern UP. Stubble burning is the easiest and cheapest way of removing residues from fields.

Residues are an important source of nutrients and organic matter and should be utilized efficiently. Though farmers perceive that burning helps control weeds, insects and diseases, it results in loss of nutrients and active soil C, leading to increased costs and soil structure decline. It also causes pollution leading to global warming and health concerns. Residue incorporation can increase N tie up and may release phytotoxins causing harmful effects on succeeding crops. These findings will assume greater importance when wheat is grown immediately after rice and with minimal cultivation. However, there is no direct evidence of deleterious effects due to phytotoxins released during rice straw decomposition on the growth and yield of wheat in the IGP. If the straw is ploughed in or is given time to decompose near the soil surface before the next crop is sown, the risk of damage seems to be much lower. The most viable option is to retain residue in the field and burning should be avoided.

Irrigation management in rice-wheat systems

Rice is kept submerged for a period of 2-4 weeks after transplanting. Submergence helps crop establishment and weed control. In coarse-textured soils, subsequent irrigations are given every second day. This practice saves a substantial amount of water without any negative effects on yield. In Punjab and Haryana, due to scarcity of labor during the transplanting season, farmers transplant in mid-May when the evaporative demand is very high. This increases the water requirement of rice that is met generally using underground water resources. Studies have shown that high intensity puddling coupled with intermittent flooding and matching of transplanting time with a lower evaporative demand period increases irrigation efficiency for these areas (Singh et al. 2001). However, alternative soil management options for efficient water management for rice are available. Such options include soil compaction, bed and furrow systems, and unpuddled direct-seeded rice. Rice grown on beds avoids water required for puddling, results in uniform application/distribution of water in the field, and should help reduce evaporation.

In the IGP, wheat is generally sown after a pre-seeding irrigation. A total of 3 to 5 irrigations is applied during the growing season depending upon soil type and rainfall pattern. The first irrigation to wheat is applied 3-4 weeks after seeding. This irrigation has special significance as it reduces soil strength, promotes root proliferation, and counters water and nutrient stress. Subsequent irrigations are based on the deficit irrigation technique to 0.9 open pan evaporation (Prihar et al. 1974). Irrigation calendars that are available for irrigation scheduling ensure efficient utilization of both the applied and soil-stored water.

Raised bed and furrow irrigation for rice-wheat system

The conventional (flat) system of planting rice and wheat with flood irrigation is a common practice in the IGP. Some of the major problems encountered with this system are excessive leaching loss of nutrients, especially N, and poor aeration. Recent studies have shown that wheat can be successfully grown on raised beds in various parts of world, including northwest India and northeast Pakistan. The optimum size of beds for wheat in the IGP has been found to be 67.5 cm (37.5 cm bed top, 30 cm wide furrows and 15-20 cm high) with two rows (20 cm apart) per bed (S.S.Dhillon, 2000). With bed planting, seed rate and irrigation water requirement can be reduced by about 30% as compared to conventionally tilled flat layouts. This system also provides an option for drilling of fertilizers between two rows of wheat both at sowing and one month after sowing. Keeping in view the increasing scarcity of irrigation water and options for diversification thorough timely planting of crops in the IGP, it has recently been proposed to develop technology for growing rice and wheat on permanent beds. Shifting rice and wheat from flats to beds will, however, involve significant changes in the movement and distribution of water in the soil profile and will influence N transformations and losses, and fertilizer N-use efficiency. Therefore, it will be worth considering the possible changes in water and N fluxes on raised beds and flats grown to rice and wheat crops in sequence. Such considerations will help construct, calibrate, and validate simulation model(s) for growth, water, and N dynamics for rice-wheat systems on flats and beds.

Possible changes in fluxes of soil water and N, and integrated nutrient management and rice and wheat growth on flats and beds are summarized in Tables 1 and 2. Though generally applicable to the entire IGP of south Asia, they are particularly relevant to coarse- to medium-textured soils of the Indian Punjab.

Table 1. Possible changes in soil water, nitrogen, and nutrient management, and rice growth on flats and beds.

Flats	Raised beds
Soil and water management	
Puddled TPR or non-puddled DSR	Non-puddled: There could be three situations: a) Permanent consolidated beds b) Permanent consolidated beds tilled at edges to facilitate transplanting c) Permanent partially tilled beds
Uncontrolled traffic causing soil compaction and structural deterioration	Controlled traffic in furrows may help structural regeneration
Flood irrigation	Irrigation in the furrows only
Complete submergence for 15-30 days after transplanting followed by intermittent flooding 2 days after drainage	Frequent irrigations to keep the furrows wet
Uniform wetting during most part of the growing season	Non-uniform wetting in beds and furrows during part or most of the growing season
Saturated surface soil during most part of the growing season	Unsaturated surface soil on the beds during part or most of the growing season
Unsaturated subsurface water flow in the subsurface soil	Unsaturated subsurface water flow in the subsurface soil
Low percolation rates	High percolation rates in the furrows
High soil water retention and low drainage rates in the puddled layers	High permeability on bed surface
Almost uniform soil evaporation from the entire area	Differential evaporation from the beds and furrows
Crop growth	
Plant growth generally not limited by water stress	Plants may suffer water stress
Transplanted rice – generally uniform crop cover	Transplanted rice on edges of the beds – may have non uniform crop cover
Uniformly distributed roots down to 40 cm depth	Non-uniform root growth under beds and furrows
Adequate weed control through water management, puddling and herbicides	Weeds could be a serious problem

Solar radiation interception - generally uniform, but may lower than on beds	Solar radiation interception- non uniform, but generally higher than on flats; cultivar differences could exist
Nitrogen management*	
Recommended N dose: 120 kg N ha^{-1} through urea in three equal splits at 0, 21 and 42 days after transplanting	Rates and dates of application could differ
First N dose through urea**:** Mixed in the soil during last puddling	1. Urea could be drilled in the center of rice rows on the beds - should lead to decreased losses of applied N via leaching, volatilization and denitrification ; should result in increased uptake by crop plants 2. Urea could be mixed with surface soil in the bed - should lead to decreased losses of applied N via leaching but increased losses via denitrification and ammonia volatilization; should result in increased uptake by crop plants
Subsequent N doses through urea: Top dressed before applying irrigation	1. Urea top dressed on beds - - should lead to decreased losses of applied N via leaching but increased losses via denitrification and ammonia volatilization; should result in decreased uptake by crop plants **2.** Urea top dressed on beds and furrows **-** In furrows, it should lead to increased losses of applied N via leaching and denitrification, but decreased losses via ammonia volatilization; should result in decreased uptake by crop plants - In beds, it should lead to decreased losses of applied N via leaching and denitrification but increased losses via ammonia volatilization; should result in N uptake by crop plants similar to flats
Other nutrients	
No response to P application when rice follows adequately P fertilized wheat	Rice on beds may respond to P application
Low probability of Fe deficiency	High probability of Fe deficiency
Integrated nutrient management	
Technology for green manuring available	Technology needs to be worked out
Technology for animal manure management available	Technology needs to be worked out
Crop residue management options available	Technology needs to be worked out

* Losses of N and crop responses to N will be strongly influenced by soil type and water management

Table 2: Possible changes in soil water, nitrogen, and nutrient management, and wheat growth on flats and beds.

Flats	Raised beds
Soil and water management	
Wheat sown in tilled fields to disrupt soil to 10 cm depth to have a fine leveled seed bed. This operation, in northwest India and Pakistan, is generally carried out after burning rice residues Some wheat area, especially under fine-textured soils in Haryana and eastern IGP, is also under no- or reduced-tillage	Reduced tillage in permanent beds : There could be three situations: a) Permanent consolidated beds b) Permanent consolidated beds tilled at edges to facilitate seeding c) Permanent partially tilled beds
Uncontrolled traffic causing soil compaction and structural deterioration; wheat responds to deep tillage under some situations	Controlled traffic in furrows may help structural regeneration
Flood irrigation	Irrigation in the furrows only
Sown after a preseeding irrigation, require 3 to 5 post-seeding irrigations, first irrigation applied 3 to 4 weeks after seeding is critical for root growth	Frequent irrigations, but of smaller amounts, may be required
Uniform wetting	Non-uniform wetting in beds and furrows
Uniform profile wetting down to ≥ 100 cm in coarse- to medium-textured soils	Differential moisture distribution under the furrows and across the beds up to a certain depth
Generally uniform soil evaporation from the entire area	Differential evaporation from the beds and furrows
Crop growth	
Plants may suffer from aeration stresses in fine-textured soils	No aeration stresses irrespective of soil
Uniform crop cover	Differential crop cover
Uniformly distributed roots down to ≥ 150 cm in coarse- to medium-textured soils	Non uniform root growth under beds and furrows
Solar radiation interception – generally uniform	Solar radiation interception – non uniform but higher than on flats; cultivar differences could exist
Adequate weed control through herbicides; chances of herbicide resistance	Mechanical weed control possible
Nitrogen management in wheat*	
Recommended N dose: 120 kg N ha^{-1} through urea; two equal splits, one at seeding, and another together with first irrigation at 3-4 weeks after sowing	Rates and dates of application could differ
First N dose through urea**:** Mixed in the soil at seeding	1. Urea drilled in the center of wheat rows on the beds - should lead to decreased losses of

	applied N via leaching, volatilization and denitrification; should result in increased uptake by crop plants 2. Urea mixed with surface soil in the bed - - should lead to decreased losses of applied N via leaching and denitrification and increased losses via ammonia volatilization; should lead to decreased uptake by crop plants
Subsequent N doses through urea: Top dressed before applying irrigation	1. Urea drilled in the center of wheat rows on the beds - should lead to decreased losses of applied N via leaching, volatilization and denitrification, should lead to increased uptake by crop plants 2. Urea top dressed on beds - - should lead to decreased losses of applied N via leaching and increased losses via denitrification and ammonia volatilization; should lead to decreased uptake by crop plants **3.** Urea top dressed on beds and furrows **-** should lead to increased losses of applied N via leaching and denitrification and decreased losses via ammonia volatilization; should lead to decreased uptake by crop plants
Other nutrients	
Drilling of 26 kg P ha^{-1} at seeding	Amount and method of P application needs to be worked out
Possibility of Mn deficiency in very coarse-textured soils	Possibility of Mn deficiency may decrease under bed and furrow system
Integrated nutrient management	
Crop residue management options available	Technology needs to be worked out.

* Losses of N and crop responses to N will be strongly influenced by soil type and water management

References

Aulakh MS, Bijay-Singh (1997). Nitrogen losses and N-use efficiency in porous soils. *Nutrient Cycling in Agroecosystems* **47,** 197-212.

Aulakh MS, Khera TS, Doran JW, Bronson KF (2001). .Denitrification, N_2O and CO_2 fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and legume green manure. *Biology and Fertility of Soils* **34,** 375-389.

Bijay-Singh, Sekhon GS (1976). Nitrate pollution of ground water from nitrogen fertilizers and animal wastes in the Punjab, India. *Agriculture and Environment* **3,** 57-67.

Bijay-Singh, Sadana US, Arora BR (1991). Nitrate pollution of ground water with increasing use of nitrogen fertilizers in Punjab, India. *Indian Journal of Environmental Health* **33,** 516-518.

Connor DJ, Timsina J, Humphreys E (2002). Prospects for permanent beds for rice-wheat systems. ASA Special Book. ASA-SSSA-CSSA. USA (in press).

Dhillon SS, Hobbs PR, Samra JS (2000). Investigations on bed planting system as an alternative tillage and crop establishment practice for improving wheat yields sustainably. Paper presented at 15th Conference of International Soil Tillage Research Organisation held at Fortworth, Texas, USA from 2-7 July, 2000.

Fertiliser Association of India (1999). Fertiliser Statistics 1997-98. New Delhi, India: Fertiliser Association of India. 396 pp.

Gajri PR, Arora VK, Prihar SS (1992). Tillage management for efficient water and nitrogen use in wheat following rice. *Soil and Tillage Research* **24,** 167-182.

Huke R, Huke E (1992). Rice-wheat Atlas of South Asia. IRRI, Los Banos, Philippines.

Katyal JC, Bijay-Singh, Vlek PLG, Buresh RJ (1987). Efficient nitrogen use as affected by urea application and irrigation sequence. *Soil Science Society of America Journal* **51,** 366-370.

Katyal JC, Bijay-Singh, Vlek PLG, Craswell ET (1985). Fate and efficiency of nitrogen fertilizers applied to wetland rice II. Punjab, India. *Fertilizer Research* **6**, 279-290.

Ladha JK, Fischer KS, Hossain M, Hobbs PR, Hardy B (2000). Improving the productivity of rice-wheat systems of the Indo-Gangetic Plains: A synthesis of NARS-IRRI partnership research. IRRI Discussion Paper No. 40.

Meelu OP, Saggar S, Maskina MS, Rekhi RS (1987). Time and source of nitrogen application in rice and wheat. *Journal of Agricultural Sciences, Cambridge* **109,** 387-391.

Narang RS, Virmani SM (2001). Rice-wheat cropping systems of the Indo-Gangetic plain of India. Rice-Wheat Consortium Pap. Ser. 11. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India.

Prihar SS, Gajri PR, Narang RS (1974). Scheduling irrigation to wheat using pan evaporation. *Indian Journal of Agricultural Sciences* **44,** 567-571.

Singh KB, Gajri PR, Arora VK (2001). Modelling the effect of soil and water management practices on water balance and performance of rice. *Agricultural Water Management* **49,** 77-95.

Timsina J, Connor DJ (2001). Productivity and management of rice-wheat systems: issues and challenges. *Field Crops Research* **69**, 93-132.

Yadav RL, Gangwar KS, Prasad K (1998). Dynamics of Rice-Wheat Cropping Systems in India. Tech. Bull. Project Directorate for Cropping Systems Research, Modipuram, India, 90 pp.

Yadvinder-Singh, Bijay-Singh (2001). Efficient management of primary nutrients in the rice-wheat system. *Journal of Crop Production* **4**, 23-86.

Testing and application of CERES-rice and CERES-wheat models for rice-wheat cropping systems

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Introduction

Rice and wheat are grown in sequence on the same land during a single year on almost 26 Mha in South and East Asia to meet the food demand of over 2 billion people. In some areas the rice-wheat (R-W) system includes crops such as mungbean, cowpea, chickpea, mustard, jute, sweet potato, and potato in the sequence. The complexity of the cropping system is further increased by the very different cultural practices for rice and wheat. The repeated transitions from anaerobic conditions under rice to aerobic conditions under wheat affect soil water movement, soil structure, nutrient dynamics, management of weeds, insects, diseases and other pests, and the growth and development of the component crops (Timsina and Connor 2001).

Two aspects of the R-W system stand out: firstly, the puddling and bunding of rice fields and their effect on the following wheat and other crops in the sequence, and second, the environment – subtropical to warm tropical climate characterized by cool dry winters, and warm, wet summers. The latter, combined with the dynamics of the R-W system, demand timely planting and harvest of the component crops. Delays, particularly in transplanting of rice due to late onset of monsoon or socioeconomic factors (e.g. labor shortage) or delay in rice harvest due to seasonal drought or other factors, will delay the sowing of wheat with dire consequences for yield. Delayed sowing of wheat causes the wheat crop to flower and fill grain during very high temperature conditions. These conditions lead to a shortened grain filling period with less opportunity to capture radiation. This shortened grain filling duration and the possibility of high temperature induced sterility results in reduced yields (Midmore et al. 1984; Saunders and Hettel 1994). Hence optimum planting date and selection of appropriate cultivars for both rice and wheat are critical for the success of the R-W system. There is a considerable role for a cropping sequence model to evaluate choices of different rice and wheat cultivars and planing dates. These models can also help to identify attributes of cultivars which better fit these environments. These attributes particularly relate to duration, yield formation processes and tolerance to stresses.

Much has been written on the inimical nature of traditional rice culture to the productivity of other crops in the R-W system (Gajri et al. 1992; Timsina and Connor 2001; Connor et al. 2002).

© 2002 CSIRO. Published in Humphreys, E., and Timsina, J. (Eds.) (2002). *Modelling irrigated cropping systems, with special attention to rice-wheat sequences and raised bed planting.* Proceedings of a Workshop, CSIRO Land and Water, Griffith, NSW, Australia, 25-28 February 2002. CSIRO Land and Water Technical Report 25/02.

Rice grown using traditional practices of land preparation can be very demanding in its water requirement. Water is required for puddling operations prior to establishment of the rice crop. These puddling operations involve destruction of soil structure in the surface layers and the formation of a less permeable layer below the surface The traditional puddled transplanted rice (TPR) culture, however, offers the following benefits: reduced percolation rate, less weed-pressure, optimization of soil pH, improved availability of P, and build-up of organic matter (more carbon sequestered). In addition to more water requirement for land preparation for TPR compared to that for direct-seeded rice (DSR), TPR may also have higher labour requirement for puddling and transplanting and, as mentioned above, detrimental effects on other crops following rice. DSR, however, generally has higher weed pressure. The move from TPR to DSR on raised-bed should not ignore the efficiency of water distribution and application systems.

Changes in rice cultural practices will, to some extent, modify the nature and extent of soil physical changes and the aerobic-anaerobic-aerobic cycle in puddled versus non-puddled system. The anaerobic-aerobic cycles may occur more frequently under a DSR and raised-bed system than with TPR where the soil remains anaerobic most of the time. The need to quantify these flooding and drying cycles and their impact on water and N dynamics, crop growth, and the environment is essential. A dynamic soil-crop model that captures the above processes/phenomena has benefits in terms of improving our current understanding and identifying knowledge-gaps, and in illustrating the advantages and tradeoffs associated with management changes both in the short-term and long-term (sustainability). This paper describes the CERES rice and wheat models and the CROPGRO model under DSSAT (Decision support system for agrotechnology transfer) for simulating rice-wheat sequences as an example of existing models that have the capacity to simulate some of the key features of the R-W system.

Model description

The CERES rice and wheat models simulate the growth, development and yield of a component crop growing on a uniform area of land under prescribed or simulated management as well as the changes in soil water, C and N that take place under the cropping system over time. The models consider the effects of weather, genetics, soil water, soil C and N, and management in single or multiple seasons and in crop rotations at any location where minimum inputs are provided. The minimum data sets for operation, calibration and validation of rice and wheat models, grown either singly or in sequence, are provided by Hunt and Boote (1994), and are summarized in Table 1.

Phenology

The phenology component of CERES–Wheat and CERES-Rice has been described elsewhere (Ritchie et al. 1998; Ritchie and NeSmith 1991; Singh 1994). It has been widely tested in a diverse range of environments and has been adopted as the basis for phenology in other crop models, eg APSIM–Wheat. The models describe the progress through the crop life cycle using a degree-day accumulation (heat sum). The duration of certain stages varies with cultivars, and coefficients are used as inputs to describe these differences. In wheat, the duration from emergence to terminal spikelet formation is influenced by vernalization (chilling requirement) and photoperiod. Cultivars differ in their vernalization requirements and their sensitivity to photoperiod, and coefficients are used to describe these sensitivities. In rice, a developmental phase (juvenile stage) occurs where the crop is not sensitive to photoperiod. After this stage sensitivity to photoperiod as well as temperature determine the time to panicle initiation. Coefficients describing this sensitivity to photoperiod as well as thermal time required for key growth stages are used to define differences between cultivars. The growth stages simulated by CERES-Rice and CERES-Wheat are indicated in Table 2. The suite of genetic coefficients used in phenology and growth simulation for each of rice and wheat are shown in Table 3.

The phenology component also simulates the effect of water or N deficit on rate of life cycle progress (Singh et al. 1999). These effects may vary with life cycle phase; for example, water deficit may slow the onset of reproductive growth but accelerate reproductive growth after beginning of grain-filling stage. For additional information on phenology in CERES-Wheat and CERES-Rice, see papers by Ritchie et al. (1998), Ritchie and NeSmith (1991), and Singh (1994).

Table 1. Minimum data required for operation and evaluation of CERES rice and wheat models

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Operation

Site (latitude, longitude, elevation, slope, aspect, water table depth)
Weather (daily maximum and minimum temperatures, global solar radiation, rainfall, wind, dew point temperatures or relative humidity)
Soil (classification using the local system and (to family level) the USDA-NRCS taxonomic system), root growth factor, drainage coefficient)

Physical properties - Depths of layers; percentages of sand, silt, and clay, and bulk density at various depths; moisture content at lower limit (LL, 15 bars), drained upper limit (DUL, 1/3 bar), and at saturation (SAT) for various depths (if they are not available, they could be estimated from percentages of sand, silt, and clay and bulk density).

Chemical properties - pH; organic C; total N; CEC

Initial conditions (C:N ratio and weight of root and shoot residues of previous crop incorporated or retained in field; date and depth of residue (material type, amount, and N concentration) incorporation; soil water, and KCl-extractable ammonium and nitrate N by soil layer); in-crop season (ammonium and nitrate N); between phases (organic C and total N); tillage practice.

Management

Rice:
Establishment - Dates of planting/transplanting; age of transplants; seedling (seedbed) environment temperature; plant population (number of plants for DSR; number of seedlings per hill for TPR)

Water - Bunding (date, and depth); flood water depth (date, and depth); depth of furrows and of flood water (for beds); irrigation amount and dates; date of water removal; percolation rate (beds- from bed surface and furrows); perched water table depth (beds- from bed surface and furrows)

Others – N fertilizer schedules, source, amount, and depth and placement of incorporation

Wheat:
Establishment – Planting date, depth and method, row spacing and direction, plant population

Water and N - Irrigation amount (or depths) and schedules; N fertilizer schedules, source, amount, and depth of incorporation

Calibration and validation (data from separate experiments): All of the above plus:

Phenology (across sowing dates and locations)

Wheat: Date of emergence, 50% flowering, physiological maturity (as identified by nodes and constant weight of grain), and harvest.

Rice: Date of emergence, PI, 50% heading, 50% flowering, physiological maturity (as identified by nodes and constant weight of grain), and harvest.

Information on phenology is required for calculation of genetic coefficients (see Table 2).

Performance at harvest (grain and straw yields, panicles or spikes per unit area, grain number per panicle, grain weight, and N concentrations of grain and straw)

Number of leaves produced in main stem; LAI, canopy dry weight (also leaf, stem, and panicle weight separately), solar radiation interception, and N concentration in above-ground biomass at key stages such as end of tillering, 50% flowering, and maturity (beds - radiation interception at edges and in centers)

Soil water content at various depths with time (beds - in bed centers and edges, and in furrows; during rice season - depth of water in furrows measured daily and immediately after and before irrigation)

Soil nitrate and ammonium content at various depths with time (beds - in bed centers and edges, and in furrows)

Table 2. Growth Stages Simulated by the DSSAT CERES-Rice and Wheat Models

Rice	**Wheat**
Germination	Germination
Emergence	Emergence

End of Juvenile	
Panicle Initiation	Terminal Spikelet
50% Heading	End ear growth
50% Flowering	
Beginning grain fill	Beginning grain fill
Maturity	Maturity
Harvest	Harvest

Table 3. Genetic Coefficients for the DSSAT CERES-Rice and Wheat Models

A. Rice	
P1	Time period in growing degree days (base 9^{o}C) from emergence to end of juvenile phase
P2R	Photoperiod sensitivity (degree day delay per hour increase in daylength)
P2O	Critical photoperiod or longest daylength (h) at which development occurs at maximum rate. At values higher than P2O the development rate is slowed (depending on P2R)
P5	Degree days (base 9^{o}C) from beginning of grain-filling (3-4 d after flowering) to physiological maturity
G1	Potential spikelet number coefficient as estimated from number of spikelets per g main culm + spike dry weight at anthesis (#/g)
G2	Single dry grain weight (g) under nonlimiting growing conditions
G3	Tillering coefficient (scalar value) relative to IR64. A higher tillering cultivar will have values greater than 1
G4	Temperature tolerance coefficient. Usually 1.0 for cultivars grown in normal environment. G4 for japonica type rice grown in warmer environments would be > 1.0. Tropical rice grown in cooler environments or season will have G4 < 1.0
PHINT	Degree days required for a leaf tip to emerge (phyllochron interval) under ideal conditions
B. Wheat	
P1D	Relative amount development is slowed for photoperiod shorter than optimum (20 h)
P1V	Relative delay in development rate for each day of unfulfilled vernalization
P5	Relative grain filling duration where each unit increase over zero adds 20 degree days to an initial value of 430 degree days
G1	Kernel number per unit stem + spike dry weight at anthesis (#/g)
G2	Potential kernel growth rate (mg^{-1} kernel^{-1}day^{-1})
G3	Tiller death coefficient. Standard stem + spike weight when elongation ceases (g)
PHINT	Thermal time between the appearance of leaf tips

Growth

The models predict daily photosynthesis using the radiation-use efficiency approach as a function of daily irradiance for a full canopy, which is then multiplied by factors ranging from 0 to 1 for light interception, temperature, leaf N status, and water deficit. There are additional adjustments for CO_2 concentration, specific leaf weight, row spacing, and cultivar (Ritchie et al. 1998). Growth of new tissues depends on daily available carbohydrate and partitioning to different tissues as a function of phenological stage and modified by water deficit and N deficiency. Leaf area expansion depends on leaf appearance rate, photosynthesis and specific leaf area. Leaf area expansion is more sensitive to temperature, water deficit, and N stress. During seed fill, N is mobilized from vegetative tissues. As a result, vegetative tissue N concentration declines and this in turn lowers photosynthesis and causes leaf senescence to increase. Protein and carbohydrate mobilized from vegetative tissue contribute to seed growth while photosynthesis declines (Godwin and Singh 1998). Cultivar differences in yield components, tillering, and temperature tolerance are captured by the model using a suite of coefficients specific to a cultivar.

Water balance

The soil water balance model developed for CERES-Wheat has been adapted by all of the DSSAT v3.5 crop models (Ritchie 1998). This one-dimensional model computes the daily changes in soil water content by soil layer due to infiltration of rainfall and irrigation, vertical drainage, unsaturated flow, soil evaporation, plant transpiration, and root water uptake processes. The soil has parameters that describe its surface conditions and layer-by-layer soil water holding and conductivity characteristics. The model uses a "tipping bucket" approach for computing soil water drainage when a layer's water content is above a drained upper limit parameter.

Drainage of water through the profile is first calculated based on an overall soil drainage parameter assumed to be constant with depth. The amount of water passing through any layer is then compared with the saturated hydraulic conductivity of that layer. If the saturated hydraulic conductivity of any layer is less than computed vertical drainage through that layer, actual drainage is limited to the conductivity value, and water accumulates above that layer. This feature allows the model to simulate poorly drained soils and perched water tables.

CERES-Rice adds to this the simulated effect of the presence of a bund. Floodwater depth, runoff (when floodwater depth exceeds bund height) and evaporation from floodwater are simulated. The model also simulates the effect of changes in percolation rate and bulk density associated with puddling and the reversion to a non-puddled state. The components of the model to describe puddling effects are rudimentary and would require further work to determine how well they would work in the coarsely textured soils of NW India.

Soil organic mater and nitrogen dynamics

DSSAT has two options to simulate the soil organic matter (SOM) and N balance. First, the original SOM model in DSSAT v3.5 (Godwin and Jones 1991; Godwin and Singh 1998) and second, the SOM module developed by Gijsman et al. (2002), based on the CENTURY model (Parton *et al.* 1988, 1994). The CENTURY-based module (i) divides the SOM into more fractions, each of which has a variable C:N ratio and can mineralize or immobilize nutrients, (ii) has a residue layer on top of the soil, and (iii) considers a texture dependent decomposition rate. In addition, the N module simulates hydrolysis of urea, nitrification, ammonia volatilization, N leaching, denitrification, algal activity and floodwater pH changes, plant N uptake, grain N dynamics, and plant N stress indices (Figure 1). The floodwater N chemistry component of the model (Godwin and Singh 1991, 1998) uses an hourly time step to calculate rapid N transformations and to update soil-floodwater-atmosphere equilibria. The water and N submodels can simulate water and N balances under fully irrigated flooded conditions, rainfed conditions where rice is alternately inundated and dry, and fully upland conditions where the soil is never flooded (Singh 1994).

Global climate change simulation

Rice-wheat cropping systems may be profoundly impacted by the effects of global climate changes. Raised temperatures could markedly affect duration of key processes in the crop life cycle as well as the rates at which key growth processes such as photosynthesis and leaf expansion proceed. In addition, raised levels of CO_2 will affect certain growth processes. The DSSAT/CERES models have been used in a variety of climate change studies and thus have appropriate linkages built into the growth and water balance routines to readily examine climate change scenarios. Details of the changes involved in the models and the resulting simulations for a range of climate change scenarios are described in Rosenzweig and Iglesias (1994). Of particular relevance to the R-W project are the simulated impacts of climate change on wheat production as reported by Rao and Sinha (1994) using CERES Wheat. In all simulations with projected future climates wheat yields were smaller than for those in the current climate. In these cases the beneficial effects of raised CO_2 on crop yield were outweighed by yield reductions associated with a shortening of the wheat growing season resulting from projected temperature increases. Karim et al (1994) used CERES Rice in a similar study in Bangladesh and found similar results for rice. Timsina et al. (1997) also used CERES rice, wheat, and maize models for predicting the effects of climate change (temperature, CO_2, and solar radiation) on the productivity of rice, wheat, and maize in terai and hills of Nepal. More recent study on the vulnerability of rice and wheat yields in NW India due to future changes in climate has been conducted by Lal et al (1998) using CERES Rice and CERES Wheat. These studies pointed out the implications of changed climate scenarios for the water requirements of both crops. CERES rice has also been used as a basis for constructing a model of methane emissions (MERES) from rice fields in Asia (Matthews et al. 2000).

Validation of CERES-Wheat and CERES-Rice

Both models have been in existence for some years now and have been the subject of continuous evaluation. Earlier testing of CERES-Wheat across many locations in the world has been reported by Otter-Nacke et al. (1986). Similar though less extensive testing of CERES-Rice has been reported by Godwin et al (1990) and Singh (1994). Hundal and Prabhjyot-Kaur (1997) have evaluated CERES-wheat using eight years of field experiments in Ludhiana. They found that the model was able to predict anthesis dates within –9 to + 6 days and for physiological maturity within –6 to +3 days. Simulation of yield and yield components across a range of experimental treatments where observed grain yield varied from 3.0 to 5.2 t/ha. Additional testing of CERES rice in Kerala, India has been reported by Saseendran et al (1998), in Thailand by Jintrawet (1994), and in Australia before and after inclusion of a routine to simulate the effects of cold damage by Godwin et al. (1994). Additional examples of testing for wheat in the rice growing regions of Australia are presented in these proceedings (Godwin et al. 2002).

Simulation of nitrogen and water interactions using CERES Rice

As described previously, rice can be grown in a range of hydrological conditions. These conditions can have differing consequences for soil N transformations. The presence or absence of floodwater will markedly affect N loss processes. Comparative simulations of crops grown on beds with an aerobic surface versus crops grown in traditional flooded culture requires careful thought of how to accommodate water nitrogen interactions. Models must be constructed to accommodate conditions of recession and replenishment of floodwater and the associated turning "on" and "off" of floodwater N transformations.

In bed-farming systems there will be occasions when rice is fully flooded (anaerobic), other occasions when it is more aerobic, and various states in between. While simulation of crops on beds has not yet been attempted with CERES rice, the capacity should already exist within the model to capture the major water nitrogen interactions. As a demonstration of this capacity, some simulation results are presented below (Table 4) based on input data from the CO_2 enrichment trials conducted in Japan by Kazuhiko (personal communication).

In this study, the soil had a high percolation rate of 15 mm d^{-1}, resulting high leaching losses of 30-35 kg N ha^{-1} and somewhat lower volatilization losses of 18-20 kg N ha^{-1}. The total fertilizer N applied was 150 kg N ha^{-1}. As the moisture regime was modified from fully flooded to partially flooded/saturated to saturated/drained upper limit grain yield decreased slightly. The key changes were in water-savings and in N loss mechanism processes. In this example, because of high percolation rate, leaching was the key N loss mechanism in the flooded situation. However, with incomplete inundation, denitrification losses increased several-fold.

Table 4. Effects of water regime on grain yield and N losses as simulated by the CERES-Rice.

	Completely flooded	Flooded–partially saturated	Saturated drained upper limit
Water-saving (mm)	-	500	900
Grain yield (t ha^{-1})	6.76	6.61	6.12
N leaching (kg N ha^{-1})	32.9	36.2	33.1
Volatilization (kg N ha^{-1})	18.5	19.9	20.5
Denitrification (kg N ha^{-1})	0.5	5.2	15.5

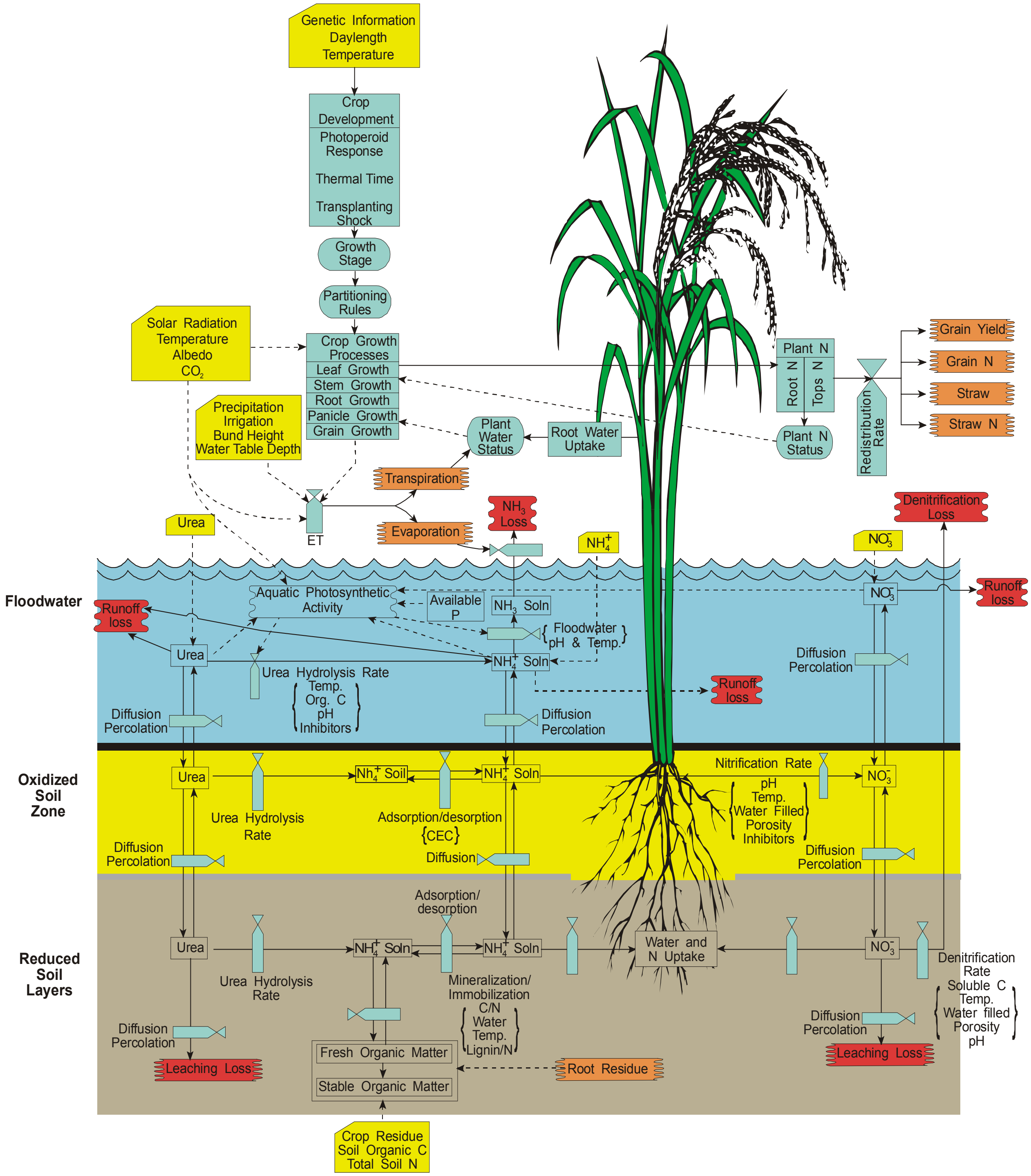

Figure 1. Schematic diagram of the CERES-Rice model.

Rice-wheat sequence

In the sequence mode of DSSAT 3.5, water, N, C, and other soil balances are simulated as a continuum, and rice, wheat, fallow (using CROPGRO) and other crops can be simulated across multiple years. One of the key features of the sequence application is quantification of the long-term changes in soil properties as a function of various crop sequence strategies. A sequence of observed historical weather data must be used when evaluating the performance of the models with data from long-term cropping sequence experiments (LTEs). For example, the sequential mode of DSSAT3.5 has been evaluated using data from a long-term R-W experiment from Pantnagar, India (Timsina et al. 1995, 1996). In this case, the weather conditions observed during the LTE period and the actual crop management practices were used as inputs for validating the R-W sequence model (Figure 2), but long-term generated weather data were used in simulating the long-term behaviour of the sequence (see Timsina et al. 1996).

The simulated yield trends in the LTE exhibited a declining trend, though not significant, for rice at both zero-N (Fig. 2) and 120 kg N ha^{-1} rates (data not shown). In contrast, the simulated wheat yield trend showed significant increases over the 15-year period at both N rates. This example illustrates the complexity of the R-W system where various factors including N rates as well as irrigation management, planting dates, choice of cultivars, etc. influenced rice and wheat yields in the sequence (Timsina et al. 1995, 1996). The CERES rice and wheat models have also been validated and applied for R-W sequences in Bangladesh (Timsina et al. 1998; Timsina and Godwin 2002).

To capture the interaction of weather with crops in any sequence and to evaluate different crop management scenarios, for example, to look at the effect of late transplanting date on rice and wheat yields in a R-W sequence one must use generated weather. A weather generator using a different “seed” or random number has to be used at the start of each sequence of weather years. For example, as shown in Fig. 3, for a 20-year maize-maize or mucuna-maize rotation with 5 replicates of weather sequence, a new random number will be used at the start of the trial– year “1990”, for each of the 5 replicates. The “replication” helps capture the variability associated with weather. The results indicate that for a coastal savanna region of West Africa, a single longer duration maize crop in rotation with mucuna yields similar to two maize crops with similar inputs of mineral fertilizers. The weather-related risks are also similar (Fig. 3). The choice of system by farmers will depend on storage of grain, stability of prices, other work opportunities, additional benefits of mucuna, etc. The modeling provided crucial information – that both systems are technically feasible.

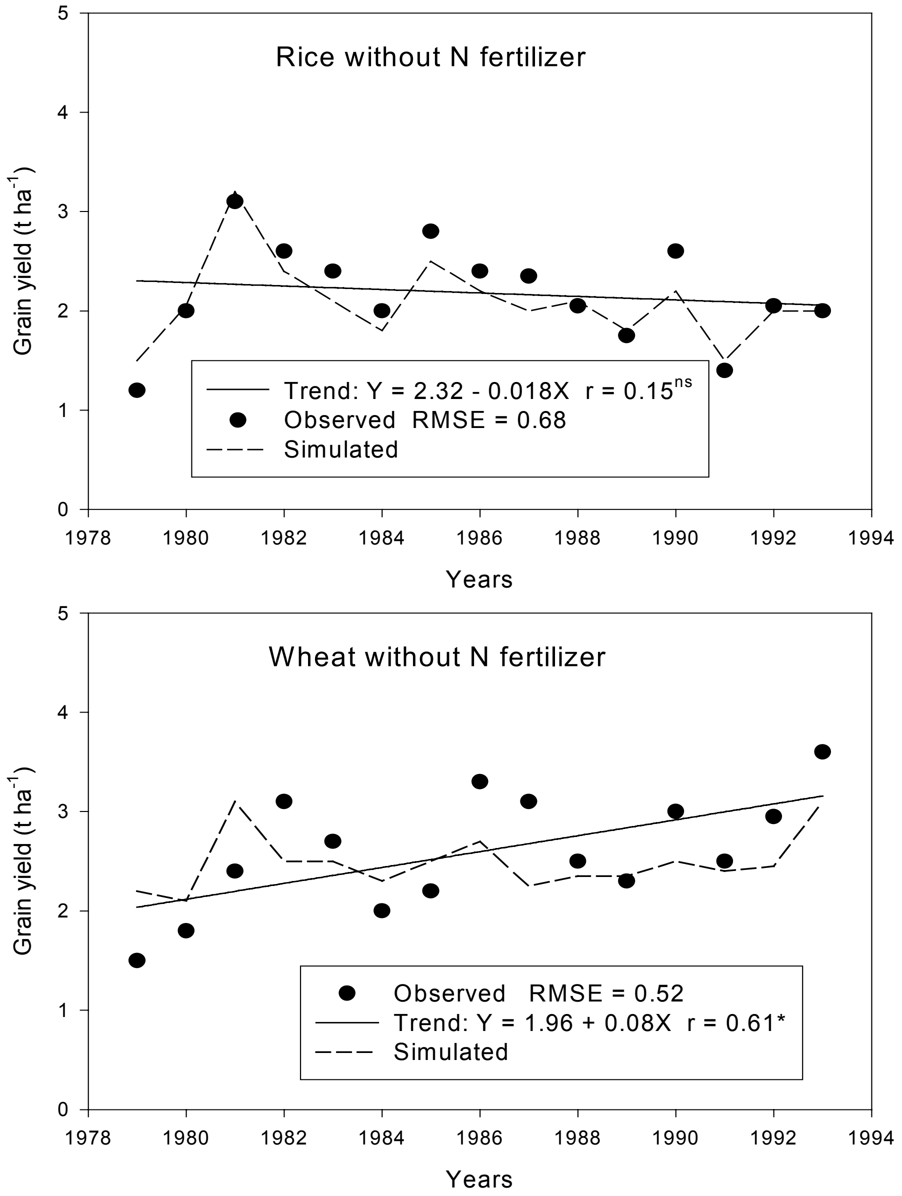

Figure 2. Observed and simulated yield trends for rice-wheat sequence at Pantnagar, India.

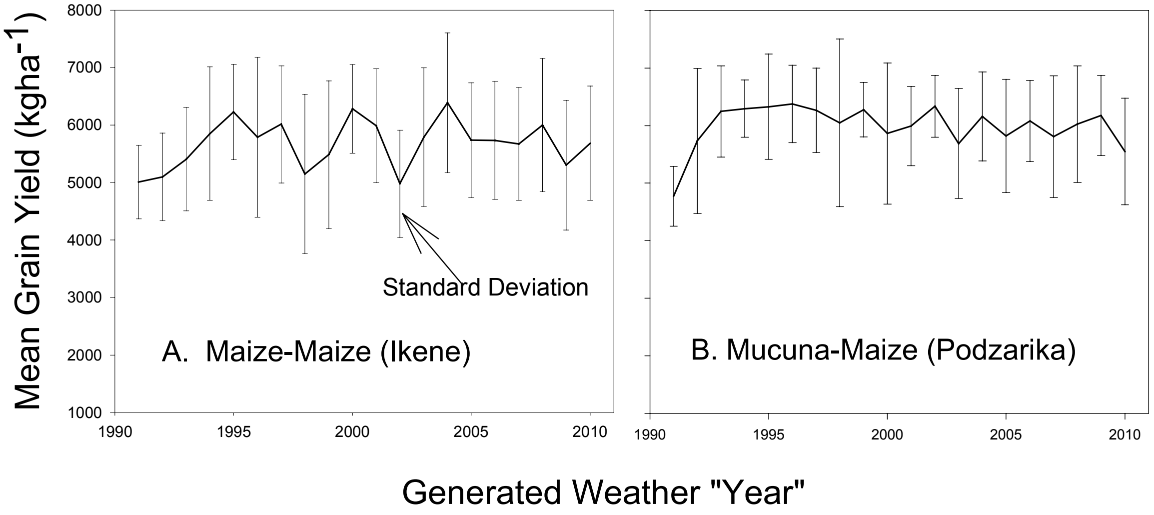

Figure 3. Comparison of cumulative (2-season) grain yield with maize-maize cropping sequence (cultivar-Ikene) versus 1-season yield from mucuna-maize system (cultivar-Podzarika).

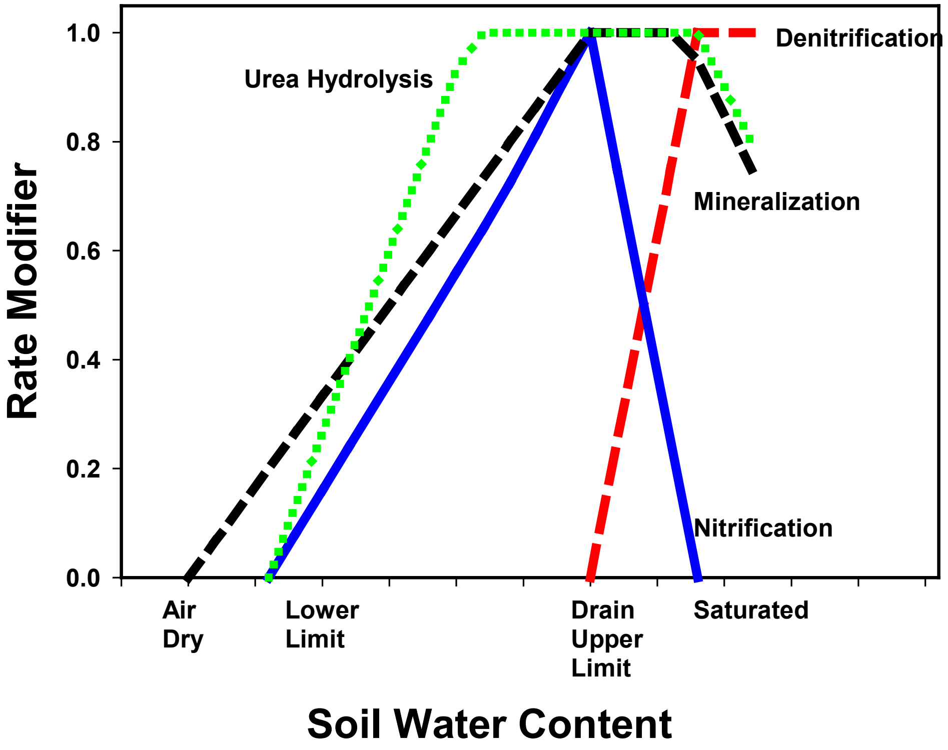

Figure 4. Rate modifiers for N transformation processes as function of soil moisture content (Adapted from Godwin and Singh 1998).

Conclusions

Increase in productivity, evaluating stability of current and proposed technologies, and quantifying sustainability are issues facing researchers, policymakers, and farmers operating the R-W system. While there are no single mechanisms or tools – a combination of crop simulation models, focused field experimentation, and thorough evaluation of past LTEs, offer the best option for tackling the above issues. Many resources (time, cost, effort, etc.) can be saved by using existing models that are capable of simulating the key bio-physical processes (water, C and N dynamics) in the R-W system. The CERES rice and wheat models under DSSAT have been tested and applied for an LTE on a R-W sequence in India and also have been tested and applied in Bangladesh. There has been widespread testing of the rice and wheat models for single crops. With the recent modifications to the model, improved capabilities exist to simulate long-term changes in SOM pools.

The tradeoffs and gains associated with any management strategy must be carefully evaluated and validated before it is implemented. It is envisaged that the CERES models, with additional validations for the R-W system, would allow reliable quantification of C, N and water balances, and grain yields under a wide range of environmental and management scenarios. Efforts, thus, should be continued in collation and generation of critical and good quality data from the R-W system to enable the calibration and validation of models for sequences.

References

Connor DJ, Timsina J, Humphreys E (2002). Prospects of permanent beds in rice-wheat systems. Improving the productivity and sustainability of rice-wheat system: issues and impact. ASA Special Book. ASA, CSSA, SSSA Publication, USA (in Press).

Gajri PR, Arora VK, Prihar SS (1992). Tillage management for efficient water and nitrogen use in wheat following rice. *Soil Tillage Research*. **24**, 167-182.

Gijsman AJ, Hoogenboom G, Parton WJ, Kerridge PC (2002). Modifying DSSAT for low-input agricultural systems, using a SOM/residue module from CENTURY. *Agronomy J.* **94(3)**, 462-474.

Godwin D, Jones CA (1991). Nitrogen dynamics in soil-crop systems. Pages 287-321. In Hanks RJ, Ritchie JT (Eds.) ‘Modeling plant and soil systems’. Agronomy Monograph 31, American Society of Agronomy, Madison, Wisconsin, USA.

Godwin D, Singh U (1991). Modelling nitrogen dynamics in rice cropping systems. Pages 287-294. In Deturck P, Ponnamperuma FN (Eds.) ‘Rice production on acid soils of the tropics’. Institute of Fundamental Studies, Kandy, Sri Lanka.

Godwin D, Singh U (1998). Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. Pages 55-78. In Tsuji GY, Hoogenboom G, Thornton PK (Eds) ‘Understanding options for agricultural production’. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Godwin, D, Humphreys, E, Smith, D, Timsina, J, Xevi, E, Meyer, W (2002). Application of SWAGMAN® Destiny to rice-wheat cropping systems. Pages 69-82, In: Humphreys, E, Timsina, J (Eds.), Modelling irrigated cropping systems, with special attention to rice-wheat sequences and raised bed planting. Proceedings of a workshop held at CSIRO Land and Water, Griffith on 25-28 February 2002. Griffith, NSW 2680, Australia.

Hundal, S.S., Prabhjyot-Kaur (1997). Application of the CERES-Wheat model to yield predictions in the Irrigated plains of the Indian Punjab. *J. Agric. Sci., Cambridge* **129**, 13-18.

Hunt LA, Boote KJ (1994). Data for model operation, calibration, and validation. In: IBSNAT: a system approach to research and decision making. Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (eds.). University of Hawaii. Honolulu, Hawaii, USA.

Jintrawet, A (1995). A decision support system for rapid assessment of lowland rice-based cropping alternatives in Thailand. *Agric. Systems* **47**, 245-258.

Karim, Z, Ahmed, M, Hussain, SG, Rashid, KB (1994). Impact of climate change on the production of modern rice in Bangladesh. In: Rosenzweig, C., Iglesias, A. (Eds.), Implications of climate change for international agriculture: crop modelling study. US Environmental Protection Agency. EPA 230-B-94-003, Washington DC.

Lal, M, Singh, KK, Rathore, LS, Srinivasan, G, Saseendran, SA (1998). Vulnerability of rice and wheat yields in NW India to future changes in climate. *Agricultural and Forest Meterology* **89**, 101-114.

Mathews, RB, Wassmann, R, Arah, J (2000). Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. I. Model development. *Nutrient Cycling in Agroecosystems*. **58**, 141-159.

Midmore DJ, Cartwright PM, Fischer RA (1984). Wheat in tropical environments. II. Crop growth and grain yield. *Field Crops Research*. **8**, 207-277.

Otter-Nacke, S, Godwin, D, Ritchie, JT (1986). Testing and validating the CERES-Wheat model in diverse environments. IFDC, Muscle Shoals, Alabama, USA.

Parton WJ, Stewart JWB, Cole CV (1988). Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry.* **5**,109-131.

Parton WJ, Ojima DS, Cole CV, Schimel DS (1994). A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. Pages 147-167. In Bryant RB, Arnold RW (Eds.) 'Quantitative modeling of soil forming processes'. Special Publication 39. SSSA, Madison, WI.

Rao, D, Sinha, SK (1994). Impact of climate change on simulated wheat production in India. In: Rosenzweig, C, Iglesias, A (Eds.) (1994). Implications of climate change for international agriculture: crop modelling study. US Environmental Protection Agency. EPA 230-B-94-003, Washington DC.

Ritchie JT (1998). Soil water balance and plant stress. Pages 41-54. In Tsuji GY, Hoogenboom G, Thornton PK (Eds) 'Understanding options for agricultural production'. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Ritchie JT, NeSmith DS (1991). Temperature and crop development. Pages 5-29. In Hanks RJ, Ritchie JT (Eds.) 'Modeling plant and soil systems'. Agronomy Monograph 31, American Society of Agronomy, Madison, Wisconsin, USA.

Ritchie, JT, Singh U, Godwin D, Bowen WT (1998). Cereal growth, development, and yield. Pages 79-98. In Tsuji GY, Hoogenboom G, Thornton PK (Eds) 'Understanding options for agricultural production'. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Rosenzweig, C, Iglesias, A (Eds.) (1994). Implications of climate change for international agriculture: crop modelling study. US Environmental Protection Agency. EPA 230-B-94-003, Washington DC.

Saseendran, SA, Singh, KK, Rathore, LS, Rao, GSLHVP, Mendiratta, N, Lakshmi Narayan, K, Singh, SV (1998). Evaluation of the CERES-Rice version 3.0 model for the climate conditions of the state of Kerala, India. *Meterol. Appl.* **5**, 385-392.

Saunders DA, Hettel GP (1994). Wheat in heat-stressed environments: Irrigated, dry areas and rice-wheat farming systems. CIMMYT, Mexico DF. 402 pp.

Singh U (1994). Nitrogen management strategies for lowland rice cropping systems. Pages 110-130. In 'Proceedings of the International Conference on Fertilizer Usage in the Tropics (FERTROP)'. Malaysian Society of Soil Science, Kuala Lumpur, Malaysia.

Singh U, Wilkens PW, Chude V, Oikeh S (1999). Predicting the effect of nitrogen deficiency on crop growth duration and yield. Pages 1379-1393. In 'Proceedings of the Fourth International Conference on Precision Agriculture'. ASA-CSSA-SSSA, Madison, Wisconsin, USA.

Timsina J, Connor DJ (2001). Productivity and management of rice-wheat cropping systems: issues and challenges. *Field Crops Research*. **69**, 93-132.

Timsina, J, Godwin D (2002). Testing and applications of CERES rice and wheat models for rice-wheat sequences of Bangladesh. *Agric. Syst.* (in preparation).

Timsina J, Singh U, Singh, Y, and Lansigan, F P (1995). Addressing sustainability of rice-wheat systems: testing and applications of CERES and SUCROS models. pp. 633-656. In: Proc. Int. Rice Res. Conf. 13-17 Feb. 1995. IRRI, Los Banos, Philippines.

Timsina J, Singh U, Singh Y (1996). Addressing sustainability of rice-wheat systems: analysis of long-term experimentation and simulation. pp. 383-397, In: Kropff et al. (Eds.) 'Applications of systems approaches at the field level'. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Timsina, J, Adhikari, B, Ganesh-KC (1997). Modelling and simulation of rice, wheat, and maize crops for selected sites and the potential effects of climate change on their productivity in Nepal. Consultancy Report submitted to Ministry of Agriculture, Harihar Bhawan, Kathmandu, Nepal. 55 pp.

Timsina J, Singh U, Badaruddin M, Meisner C (1998). Cultivar, nitrogen, and moisture effects on a rice-wheat sequence: experimentation and simulation. *Agronomy Journal*. **90**, 119-130.

Modelling growth and development of wheat and rice in APSIM

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Introduction

APSIM contains a comprehensive array of modules for simulating growth, development and yield of crops, pastures and forests and their interactions with the soil. Currently crop modules are available for barley, canola, chickpea, cotton, cowpea, hemp, fababean, lupin, maize, millet, mucuna, mungbean, navybean, peanut, pigeonpea, sorghum, soybean, sunflower, wheat and sugarcane. In addition there are general modules for forest, pasture and weed as well as specific implementations for the pasture species lucerne and stylo. Citation details for these modules are provided where available in Table 1 of Keating et al. (2002). The scientific bases of simulation approaches employed for all functional components are included in module documentation on the APSIM website (www.apsim-help.tag.csiro.au). In the majority of cases these science documents include information on module performance against observed data.

The plant modules simulate key underpinning physiological processes and operate on a daily time step in response to input daily weather data, soil characteristics and crop management actions. The crop modules have evolved from early versions for focus crops such as maize, peanut, sorghum and sunflower. The initial crop modules of APSIM utilised concepts from existing models available at the time and added concept enhancements from local research to improve existing models as required. The on-going development of crop modules in APSIM has attempted to balance support from scientific understanding with the pragmatics of requirements for prediction in applications and the regulatory framework of sound software engineering practice.

Currently in APSIM, all plant species use the same physiological principles to capture resources and use these resources to grow. The main differences are the thresholds and shapes of their response functions. Descriptions of these processes are covered by Wang et al. (2002). Many of these processes have been coded into sub-routines in a process library, held in a stand-alone module, which individual crops can call. The routines in the library are structured in separate blocks corresponding to the crop model components of phenology, biomass, canopy, root system, senescence pools, water, nitrogen and phosphorus. The sub-modules contain the science and understanding needed to simulate major functional components of crop growth and development. Crop ontogeny is simulated via relationships defining observed responses to temperature and photoperiod. Leaf area production and senescence is simulated via relationships of leaf initiation rate, leaf appearance rate and plant leaf area with temperature. Potential crop

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water uptake is simulated via relationships with root exploration and extraction potential, which depends on soil and crop factors. All coefficients for general crop responses and crop/cultivar specific coefficients are stored external to the code to allow ease of use and transition across crops/cultivars. The process library includes a number of options for modelling specific functions and processes, which have been drawn from a range of existing crop models. The ability to switch between optional processes within sub-modules or between optional entire sub-modules facilitates logical comparative analysis of modelling approaches. The process library has substantially reduced the amount of code needed for simulating multiple crops, resulting in greater transparency, more robust code with lower maintenance costs.

Externalised constants and parameters from the code are stored in crop parameter files. Each file is considered as crop species-specific. It consists of two major parts: crop-specific constants and cultivar-specific parameters. Within some individual crop species the category of a "crop class" has been developed. The crop class represents a category of crop below that of the species and is distinctly different enough to justify a separate parameter section. The separation of code and parameters makes it easy to re-parameterise an existing module for a new crop with few source code changes and significantly accelerates testing and validation procedures.

Wheat modeling in APSIM

The wheat module was developed from a combination of the approaches used in the NWHEAT (Keating et al. 2001) and I-WHEAT (Meinke et al. 1998) models of wheat. NWHEAT was a derivative of CERES-Wheat (Otter-Nacke et al. 1986), while I_WHEAT has features of the model of Sinclair and Amir (1992). Both models shared the same routines for phenological development, and had similar approaches for biomass accumulation. A derivative of NWHEAT has been extensively validated in Western Australia (Asseng et al. 1998a,b) and in other environments around the world (Asseng et al. 2000).

APSIM-Wheat was created using approaches for different crop growth processes taken from NWHEAT, I-WHEAT and in some case entirely new approaches were adopted where it was thought that the existing approaches in either model were not suitable. In some cases these approaches already exist in the APSIM crop library and are used by many of the other crop modules.

The wheat module has been validated against a wide range of data sets varying in water and N supply, locations and soil types. Main regions for testing have been the NE Australian wheat belt and the West Australia wheat belt, although there has been testing in selected international environments (Fig. 1).

Development of the Rice module

Two parallel ACIAR (Australian Centre for International Agricultural Research) projects ('*Prospects for improved integration of high quality forages in the crop-livestock systems of Sulawesi, Indonesia*' and, '*Optimising crop-livestock systems in west Nusa Tenggara Province, Indonesia*') have recently commenced in Indonesia involving the use of an integrated modeling approach to investigate the biophysical, economic and social implications of changes in forage and livestock related farming practice. A key requirement of these projects is a farming systems model that can simulate the growth, development and yield of a range of crops and forages (new and existing), residue and soil related processes, the interactions between these processes and, the responses to climate and management inputs. One shortcoming with APSIM is that it does not have a crop module for rice, the dominant annual crop in the mixed crop-livestock systems of both Sulawesi and Sumbawa (where the projects are based). This provided the impetus for the development of a rice growth and development model for use within the APSIM framework.

It was decided that APSIM Rice should be developed in two stages in order to address both the short-term objectives of the above ACIAR projects, as well as the long-term strategic interests of the APSRU group (the developers and owners of APSIM).

The above-mentioned ACIAR projects are of comparatively short duration (2 and 3 years respectively). Consequently, there is a need to develop a functioning APSIM Rice module in a short period of time, but with adequate performance under the range of growing conditions likely to prevail in the project locations. While it may be feasible to modify one of the many existing rice models to be compatible with APSIM, a more efficient approach is to take an existing module for a 'like' crop within the current APSIM crop library and re-parameterise it to represent the crop of interest. The suitability of this approach is based on the substantial physiological similarity between the template and new crop, and is amply demonstrated by the current suite of APSIM legume modules developed from a common legume template. With this in mind, it was decided to use APSIM Wheat as a template for the rice model. The method involved re-parameterising the template using published and unpublished data for rice. Values for those parameters which couldn't be found in the literature were set through calibration against 'quality' datasets. Datasets from a range of irrigation treatments (upland and lowland, irrigated and rainfed) conducted in central and southeast Queensland were used for this purpose.

It is also recognized that there are long-term strategic advantages in having a more robust and widely applicable rice modeling capability within APSIM. The second stage will aim to build on and improve the first version and will clearly involve a more substantial investment in terms of model development and testing. The intention in this second stage is to construct APSIM Rice from a library of sub-routines that are most appropriate for simulating rice growth and development, as opposed to just using wheat sub-routines (as in Stage 1). This provides more flexibility in model construction and allows for incorporation of the most appropriate simulation methodologies. It also enables the inclusion of new rice specific sub-routines e.g. the impact of transplanting on growth and development.

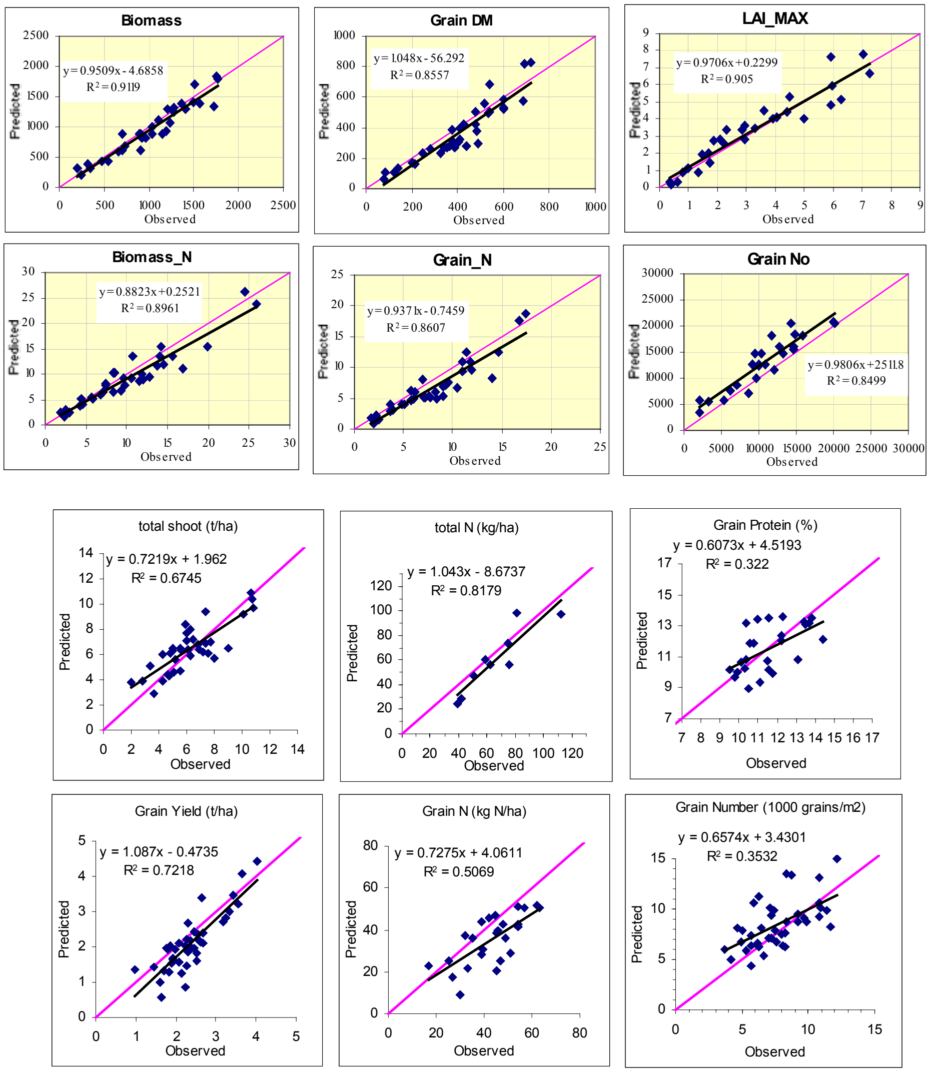
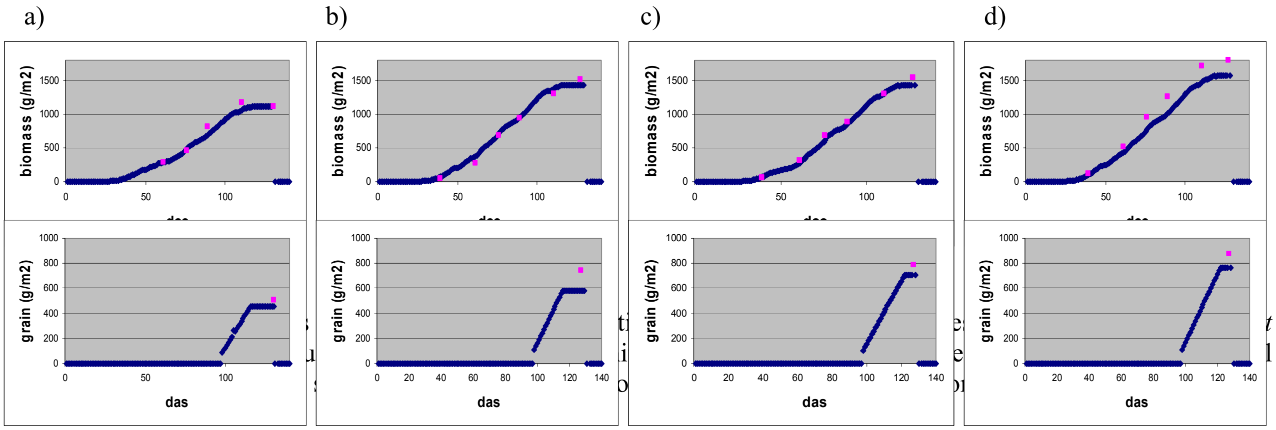


Figure 1: Agreement between observed and simulated crop attributes for datasets from Queensland and northern NSW (upper 6 panels) and West Australia (lower 6 panels).

The following figure shows example calibration plots for APSIM Rice (Stage 1) of grain yield and total above ground biomass under a range of flooded and unflooded irrigated treatments (Borrell *et al.* 1997).



References

Asseng S, Fillery IRP, Anderson GC, Dolling PJ, Dunin FX, Keating BA (1998a). Use of the ASPIM wheat model to predict yield, drainage, and NO3 leaching for a deep sand. *Australian Journal of Agricultural Research* **49,** 363-377.

Asseng S, Keating BA, Gregory PJ, Fillery IRP, Bowden JW, Turner NC, Palta JA, Abrecht DG (1998b). Performance of the APSIM wheat model in Western Australia. *Field Crops Research* **57,** 163-179.

Asseng S, van Keulen H, Sto, W (2000). Performance and application of the APSIM Nwheat model in the Netherlands. *European Journal of Agronomy* **12,** 37-54.

Borrell A, Garside A, Fukai S (1997). Improving efficiency of water use for irrigated rice in semi-arid tropical environment. *Field Crops Research*, 52, 231-248

Keating BA, Meinke H, Probert ME, Huth N, Hills IG (2001). Nwheat: Documentation and performance of a wheat model for APSIM. CSIRO Tropical Agriculture Technical Memorandum 9, 66 pp.

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCown RL, Freebairn DM, Smith CJ (2002) The Agricultural Production Systems Simulator (APSIM): its history and current capability. *European Journal of Agronomy*. (in press)

McCown RL, Hammer GL, Hargreaves JNG, Holzworth DP, and Freebairn DM (1996). APSIM: A novel software system for model development, model testing, and simulation in agricultural systems research. *Agricultural Systems*, **50,** 255-271.

Meinke H, Rabbinge R, Hammer GL, van Keulen H, Jamieson PD (1998). Improving wheat simulation capabilities in Australia from a cropping systems perspective. II. Testing simulation capabilities of wheat growth. *European Journal of Agronomy* **8,** 83-99.

Otter-Nacke S, Godwin DG, Ritchie JT (1986). Testing and validating the CERES-Wheat model in diverse environments. AGRISTARS Yield Model Development. USDA-ARS, Temple, TX.

Sinclair TR, Amir J (1992). A model to assess nitrogen limitations on the growth and yield of spring wheat. *Field Crops Research* **30,** 63-78.

Wang E, Robertson MR, Hammer GL, Carberry P, Holzworth D, Hargreaves J, Huth N, Chapman S, Meinke, H, McLean, G (2002). Design and implementation of a generic crop module template in the cropping system model APSIM. *European Journal of Agronomy* (in press).

Modelling crop sequences using APSIM

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Abstract

Simulation of sequences of crops involves more than judging crop models on their ability to predict crop yield. The carry-over effects of crops in terms of soil water and nitrogen dynamics are discussed. APSIM's ability to simulate sequences of crops is illustrated for (1) a selection of treatments from the Warra Soil Fertility Restoration Experiment (continuous wheat, wheat-chickpea and wheat-lucerne), and (2) a comparison of annual crops (sorghum and barley) with lucerne on a deep black earth at Jimbour, Qld where lucerne dried out the profile to at least 3m. Finally some comments are made on challenges to be faced in order to simulate a flooded rice-wheat system.

Introduction

In talking of crop modelling, it's all too easy to use language that refers to "a wheat model" or "a rice model" or "a model for some other crop". But the real world of farming is not composed of single crops.

The Agricultural Production Systems Simulator, APSIM (McCown et al. 1996) developed out of the recognition that crops come and go, like other aspects of management. Simulation of farming systems needs to be able to deal with sequences of crops, and in some instances mixtures of crops.

Because of this tendency to think of models of single crops, the performance of models also tends to focus on how well they predict the growth/development of individual crops. Typically, the soil conditions (water and nitrogen) are specified prior to planting together with the sowing and other management details, and then the output from the model is likely to concentrate on aspects of plant growth, and especially final yield, and how the predictions match up from what is observed.

To change the focus from a single crop to a sequence of crops (either the same crop or a rotation of different crops), is a much more demanding task. It also creates a need for data sets that are quite different from those that are used to develop/validate a model of the growth of an individual annual crop. Modelling of perennial crops (such as sugarcane or lucerne) has much in common with modelling sequences of annual crops.

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In this contribution, three things are attempted:

- The first is to outline the particular demands of modelling sequences of crops.
- The second is to show some examples of how APSIM has been, and is, being used to tackle particular situations that involve sequences of crops.
- Finally, I make some passing remarks about the particular challenges that are involved in modelling rice-wheat systems.

Modelling crop sequences

Many of the problems confronting agriculture today involve extended timescales (well beyond that of a single crop). Some examples pertinent to Australian agriculture are:

- Dryland salinization caused by deep drainage of water
- Soil acidification
- Improving N nutrition of crops through rotations with legumes
- Greenhouse abatement strategies through carbon sequestration
- Increasing water use efficiency by modifying crop rotations.

For each of these examples, there is an expectation that there is a role for modelling to analyse the problem and/or investigate possible strategies that can contribute to its solution. A common link is that they all involve sequences of crops. For models to perform in a credible fashion, the paramount requirement is that they adequately represent the manner in which one crop (under the prevailing weather) alters the soil resource, and thus creates a particular set of conditions for a following crop.

It is aspects of the water and nitrogen supply to plants that are most amenable to adjustment or control by management. Thus it is no surprise that it is water and N that are the main soil constraints that are considered in crop models, and also in farming systems models (Probert and Keating 2000).

The following paragraphs indicate the carry-over effects from the previous crop in terms of soil water and nitrogen. Of particular note is the interdependency between crop growth, the water balance, and the dynamics of N in soil.

Water

The main carry-over effect is the water remaining in the soil profile; a secondary effect will be via above-ground residues (and their management) that will alter the fate of water (runoff, evaporation) during the ensuing fallow.

A water balance that adequately represents the dynamics of water in the soil-plant system is imperative.

Crops will differ in terms of rate of root elongation and total rooting depth. This determines water use by the crop, and becomes the crucial factor in the creation of a dry soil buffer (dewatering) following a deep-rooted perennial like lucerne. But it can also be the cause of reduced growth of the following crop if there has not been adequate recharge of the soil water profile.

Some contentious issues:

- whether different crops have different lower limits of water extraction (may be confounded with fact that roots of different crops may have been growing for different lengths of time)
- how roots respond to defoliation (cutting or grazing).

Nitrogen

Carry-over effects include residual mineral-N remaining in soil, crop residues and roots, and changes in soil organic matter (that will influence future N mineralization).

Mineral-N is dependent on the soil water balance (which determines mineralisation, redistribution of nitrate in the profile, losses via denitrification) and crop N uptake.

Change in soil organic matter is related to carbon inputs into soil (also N where immobilization demand can not be met).

Crop residues and roots have major effects on N supply to following crops. Legume residues (low C:N ratio) contribute N via mineralization; cereal and other residues with wide C:N ratios cause immobilization. Rate of residue decomposition (dependent on temperature and moisture) and length of fallow are other important factors on N mineralization (cf double cropping vs several months fallow). The APSIM Residue module that deals with the decomposition of above-ground residues is quite simplistic; for example it does not keep track of different types of residues, merely averaging the properties of new and existing residues.

The requirement for satisfactory prediction of roots (amount, N content, distribution in profile, rate of senescence, sloughing of C and N) and residues (amount, N content) is a major difference between use of a model to predict yield of a single crop, and simulating behaviour of a sequence of crops. Failure to satisfactorily predict inputs of plant materials, their decomposition and associated N mineralization/immobilization often results in a strong biennial pattern in predicted crop growth; a large crop leaves much root and residues creating too much immobilization, so that following crop suffers unrealistic N stress and growth is under-predicted leading to under-prediction of residues and immobilization, so next crop gets too much N, and so the cycle continues.

Carbon

In many models (e.g. the APSIM SoilN module, Probert et al. 1998b), the dynamics of carbon and nitrogen in the crop residues and soil organic matter pools are closely linked through the C:N ratios of the soil organic matter pools.

An example focussing on soil fertility restoration

Data from the Warra Soil Fertility Restoration Experiment (Dalal et al. 1995, Strong et al. 1996) have been used extensively to validate aspects of the APSIM modelling framework, and especially its capability to simulate a sequence of crops (Probert and McCown, GRDC Final Report, Project CSC15). The experiment commenced in 1986 on a Vertosol (Typic Chromustert) that originally supported brigalow-belah vegetation, but cultivation for cereal cropping since 1935 had resulted in decline in soil organic matter and rundown of soil fertility. The experiments involved a range of treatments including continuous wheat with a range of N fertilizer inputs, rotation of wheat and chickpea, and rotations of wheat and lucerne (1 to 4 years of lucerne). The data provide opportunities to test model performance in terms of crop yields, N uptake and soil water and nitrate-N which were measured in 7 layers to 1.5m twice each year (pre-plant and post harvest).

Figures 1, 2 and 3 illustrate the generally good performance of APSIM in predicting crop performance on selected treatments in terms of yields, protein content of wheat, and soil water and nitrate-N in the 1.5m profile. In these simulations, the soil conditions (soil water, nitrate-N and soil organic matter) were initialised in May 1987 prior to the first crops being sown, and the model then simulated crop growth for the next 10 years as a continuous run. Note how lucerne, especially in 1993 and 1995, dries the soil to a greater extent than the annual crops (compare Fig. 3 with Figs 1 and 2).

Table 1 sets out the statistics for comparing model performance when the sequence of crops is predicted (initialised only in 1987) or when each crop is predicted individually (with soil water and nitrate-N re-initialized prior to planting of each crop). There is little difference in the goodness of fit, indicating that the integrity of the simulation of the soil water, nitrogen and residues in these system is being maintained over the duration of the experiment.

The capability of APSIM to simulate crop rotations, and especially rotations of cereals and legumes, has been used to explore strategies for supply of N in farming systems (e.g. legumes vs fertilizer) in Australia (Probert et al. 1998a) and offshore (eastern and southern Africa).

An example focussing on soil water

The Warra soil becomes quite acidic at depth, and this is thought to limit the rooting depth of crops, even lucerne. In other studies on the Darling Downs this is not the case. For the black earth at Jimbour, Queensland there is good evidence that lucerne extracts water to at least 3m. [Elsewhere there are reports of lucerne roots to 16m.] In contrast to lucerne, annual cropping systems with sorghum and barley do not change water content below 1.8m. The parameterisation of the soil water characteristics of the soil is shown in Figure 4 and the simulated soil water for these systems in Figure 5.

The water extraction pattern simulated shows the lucerne root front progressively moving into deeper soil layers. Whilst there is sound evidence that lucerne dries out the soil to 3m (at least), the productivity of the stand rapidly declined as the deep water resource was used up.

The capability of APSIM to model the water balance has been used to assess how alternative cropping systems (annual cropping, opportunity cropping, phase farming with lucerne, continuous lucerne) would impact on the leakiness of farming systems thus contributing to dryland salinization (Keating et al. 2001).

Some comments on rice-wheat rotations

From a modelling perspective, there are some special challenges that arise with rice-wheat systems. These are principally concerned with the regular cycling between flooded (anaerobic) and dryland (aerobic) conditions. The impaired soil structure of the puddled layer and formation of a hard pan on drying will be important to the movement of water and to the growth of roots for the following crop.

The soil organic matter/nitrogen routines in the APSIM SoilN module do differ depending on whether the water content of the soil is above or below DUL (drained upper limit). However they have not been tested under extended periods of water-logging. Particular issues will be the decomposition of soil organic matter, nitrification, and denitrification.

Currently APSIM crop modules do not include constraints to plant growth other than those involving water and nitrogen (and possibly soil effects on root elongation). Any other nutritional problems caused by cycling between aerobic and anaerobic conditions would be beyond the scope of present models.

Table 1. Statistics describing the goodness of fit for yield, N uptake etc of wheat and chickpea crops in the core experiment at Warra.

	Continuous systems			With resets for each crop		
	100xR^2	RMSD	MD	*100xR^2*	*RMSD*	*MD*
Wheat						
Total biomass (kg/ha)	71.3	1400	-303	*77.7*	*1334*	*-476*
Grain yield (kg/ha)	75.0	564	-194	*76.6*	*512*	*-223*
N in tops (kg/ha)	74.8	19.1	9.3	*78.0*	*14.7*	*4.3*
N in grain (kg/ha)	67.8	15.5	-4.3	*70.8*	*14.5*	*-6.6*
% protein (@ 12%)	29.6	2.00	-0.08	*39.4*	*1.81*	*-0.35*
Chickpea						
Total biomass (kg/ha)	80.7	777	339	*51.8*	*1021*	*273*
Grain yield (kg/ha)	78.1	360	192	*60.7*	*411*	*119*
N in tops (kg/ha)	79.3	15.7	8.6	*57.8*	*18.8*	*6.4*

The wheat data are for the continuous wheat treatments involving conventional and zero tillage and N fertilizer inputs (0 to 75 kg N/ha.yr). The chickpea data are from the chickpea-wheat rotations. The main body of the table relates to the systems that were modelled as continuous runs initialised only at the commencement of the experiment (in May 1987). For comparison, the values in italics are the corresponding data when the systems are modelled as individual crops with soil water and nitrate-N re-initialised prior to each crop using the measured data from the pre-plant soil samplings.

100xR^2 is the percentage of the total variation explained by the linear regression of predicted vs observed data. RMSD is the root mean squared deviation – a measure of the spread about the 1:1 line of perfect fit. MD is the mean deviation – a measure of any bias in the model.

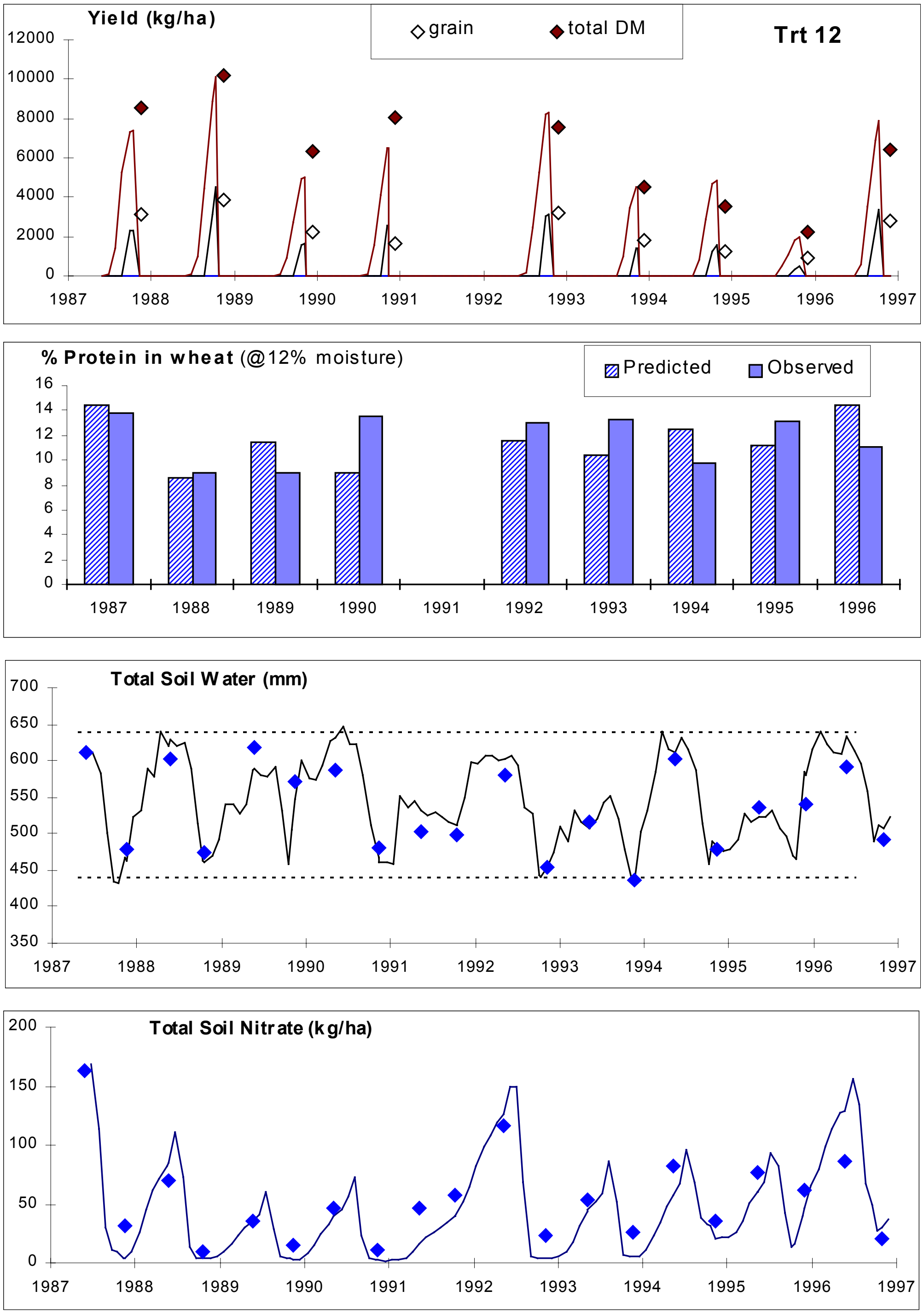

Figure 1. Simulation of yields and protein content of wheat, and soil water and nitrate-N for Treatment 12 (conventional tillage with 25 kg/ha/yr fertiliser N) in the core experiment at Warra with model initialisation only in May 1987 prior to the first crop. The symbols represent the measured data. Soil water and nitrate refer to the totals in the 0-1.5 m profile. Note the increase in nitrate-N following the application of fertiliser at sowing, and the long fallow that resulted from the "missed crop" in 1991. The dashed lines on the soil water figure show the assumed DUL and LL for wheat.

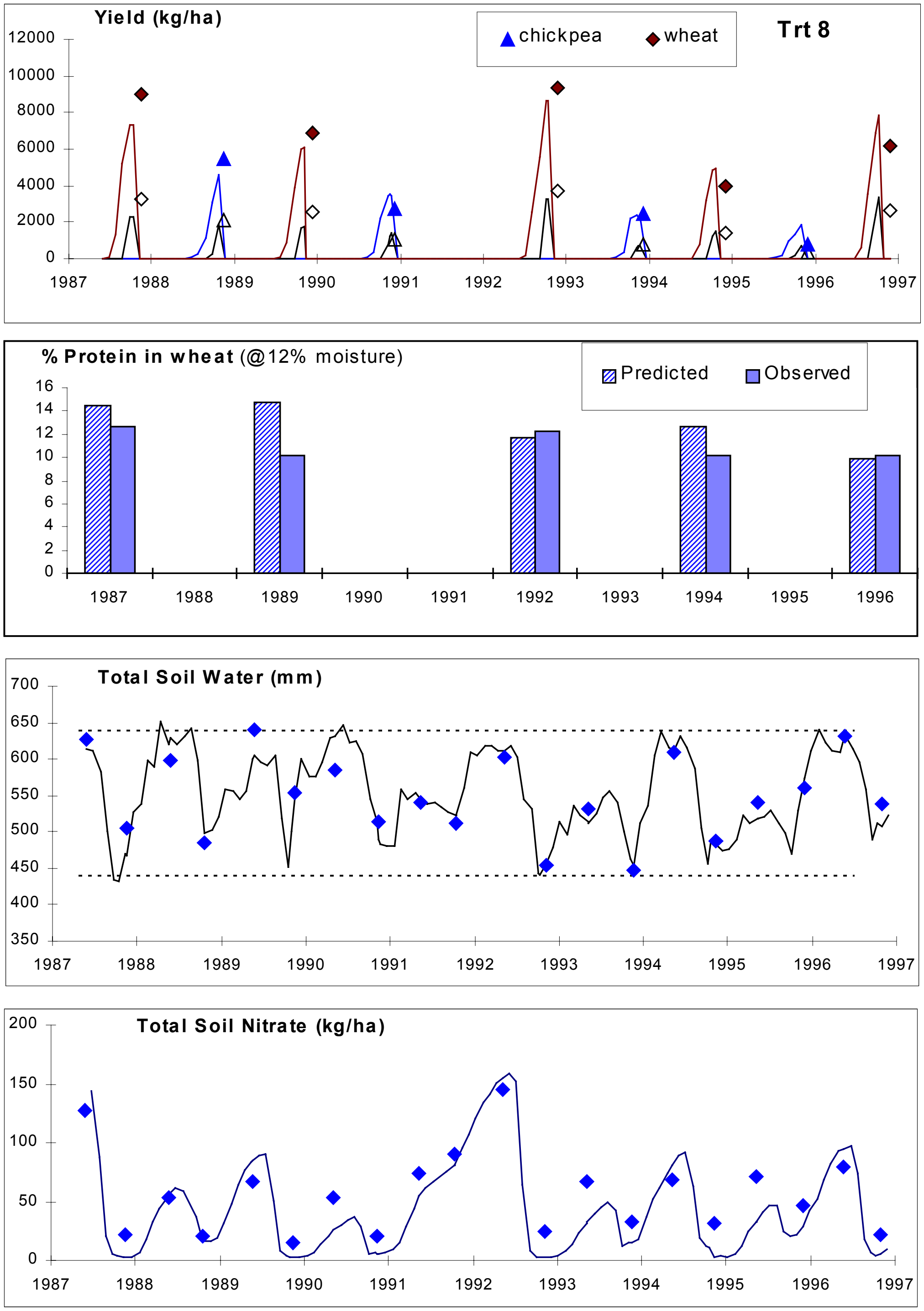

Figure 2. Simulation of total biomass and grain yields of wheat and chickpea, protein content of wheat, and soil water and nitrate-N for Treatment 8 (chickpea – wheat rotation) in the core experiment at Warra. The symbols represent the measured data. Soil water and nitrate refer to the totals in the 0-1.5 m profile. The dashed lines on the soil water figure show the assumed DUL and LL for wheat.

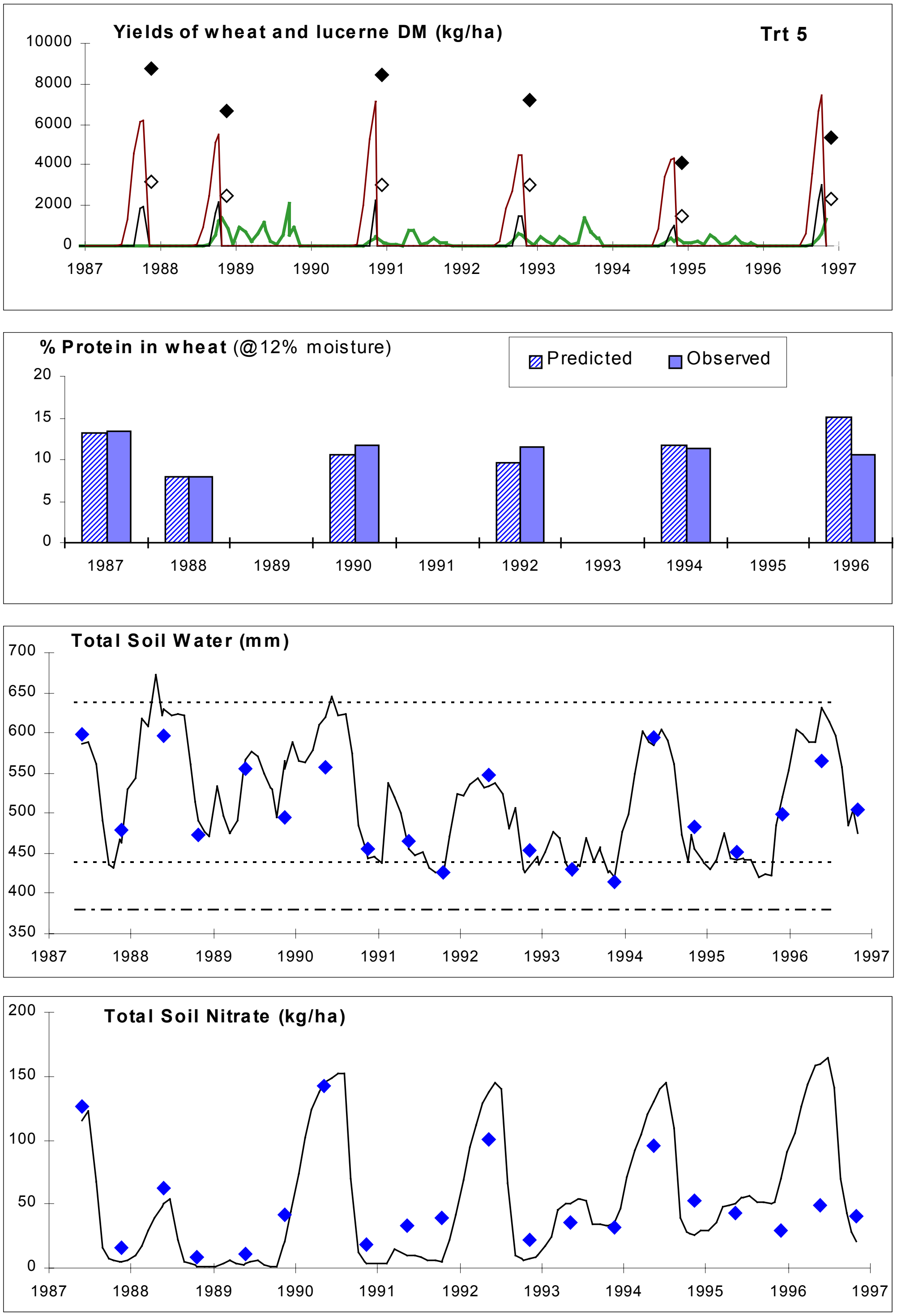

Figure 3. Simulation of wheat and lucerne yields, protein content of wheat, and soil water and nitrate-N for Treatment 5 (lucerne - wheat rotation) in the core experiment at Warra. The symbols represent the measured data. Soil water and nitrate refer to the totals in the 0-1.5 m profile. The dashed lines on the soil water figure show the assumed DUL and LL for wheat and lucerne.

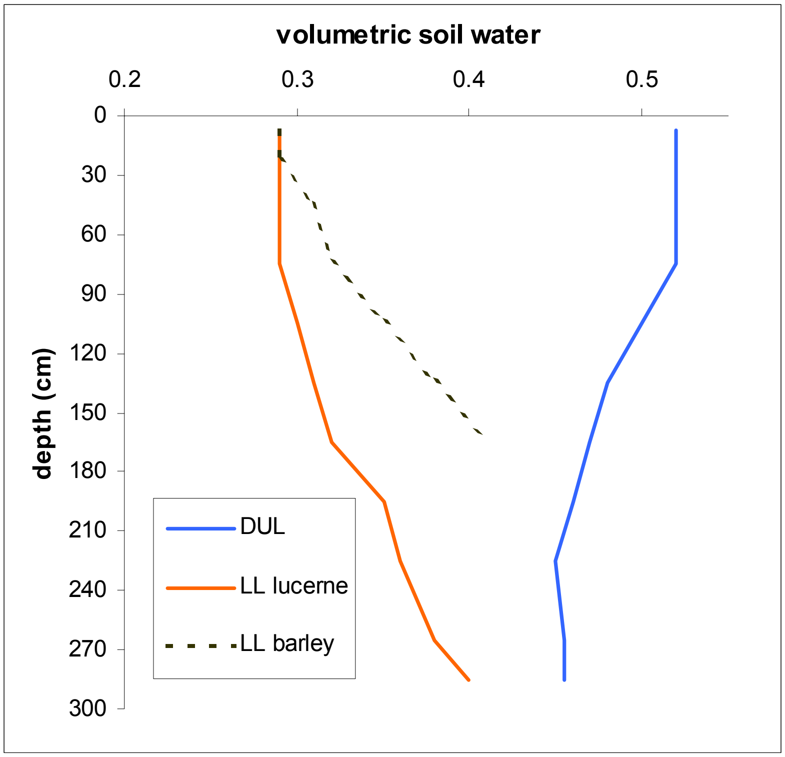

Figure 4. Parameterisation of soil water for lucerne and barley on the deep black earth at Jimbour, Qld. The rooting depth for barley was limited to 1.8m.

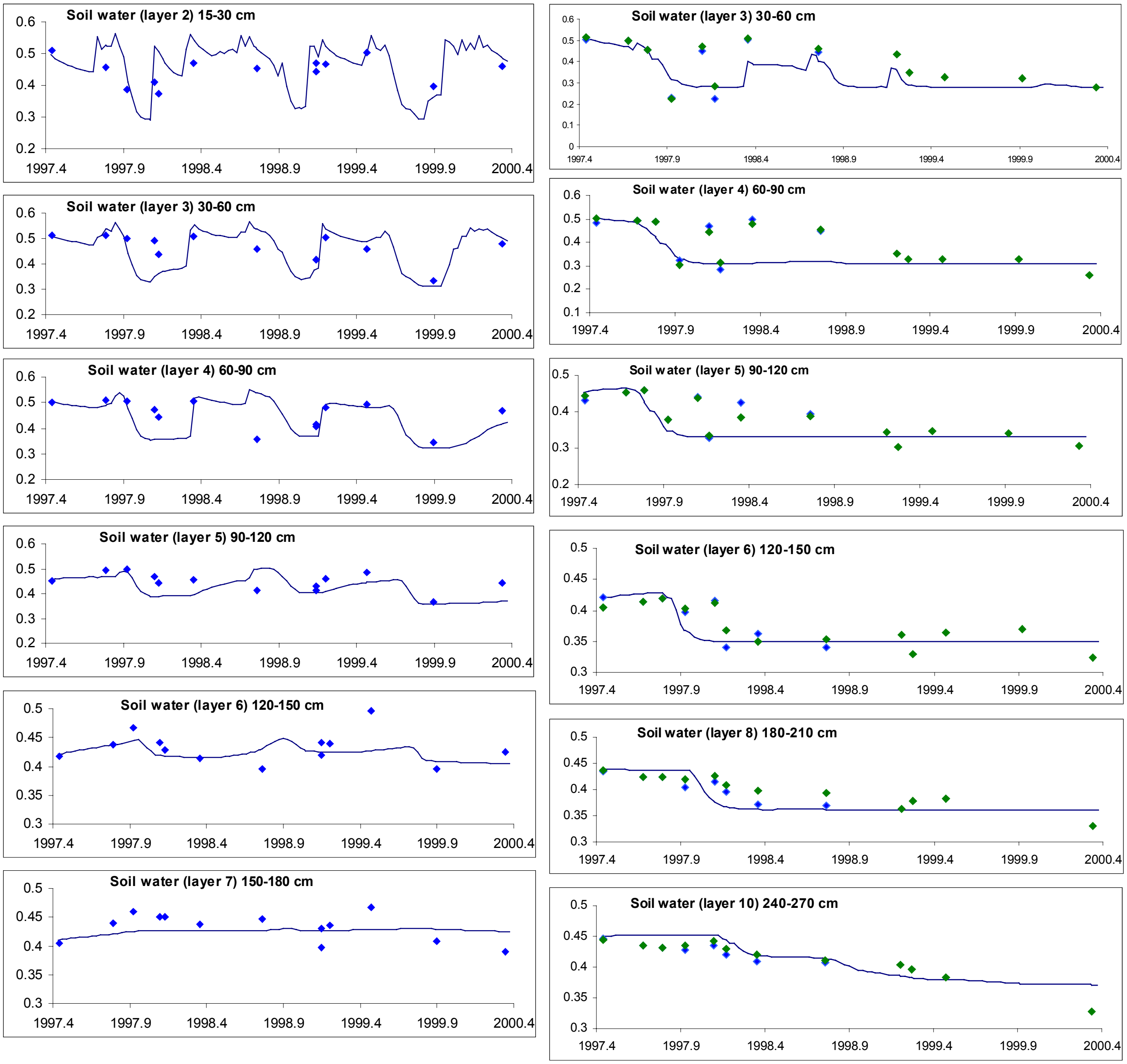

Figure 5. Measured and simulated soil water for two farming systems on a deep black earth on the Jimbour Plain, Queensland [Neal Dalgliesh, GRDC Eastern Farming Systems Project] The left hand panel of figures are for a sequence of annual crops (sorghum in 1997/98 and 1998/99, followed by barley in 1999); the right hand panel for lucerne established in 1997. Note that layers shown are not the same for the two systems.
[Observed data in first year from NMM; noise thought to be due to failure to adequately correct for soil shrinkage. In later years based on gravimetric data.]

References

Dalal RC, Strong WM, Weston EJ, Cooper JE, Lehane KJ, King AJ, Chicken CJ (1995). Sustaining productivity of a Vertisol at Warra, Queensland, with fertilizers, no-tillage, or legumes 1. Organic matter status. *Australian Journal of Experimental Agriculture* **35**, 903-913.

Keating BA, Verburg K, Smith CJ, Probert ME, Gaydon D (2001). Assessing leakiness in Australia's dryland farming systems. In 'MODSIM 2001International Congress on Modelling and Simulation', Australian National University, Dec. 2001, pp 1811-1816.

McCown RL, Hammer GL, Hargreaves JNG, Holzworth DP, Freebairn DM (1996). APSIM: A novel software system for model development, model testing and simulation in agricultural system research. *Agricultural Systems* **50**, 255-271.

Probert ME, Carberry PS, McCown RL, Turpin JE (1998a). Simulation of legume-cereal systems using APSIM. *Australian Journal of Agricultural Research* **49**, 317-327.

Probert ME, Dimes JP, Keating BA, Dalal RC, Strong WM (1998b). APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems* **56**, 1-28.

Probert ME, Keating BA (2000). What soil constraints should be included in crop and forest models? *Agriculture Ecosystems and Environment* **82**, 273-281.

Strong WM, Dalal RC, Weston EJ, Cooper JE, Lehane KJ, King AJ, Chicken CJ (1996). Sustaining productivity of a Vertisol at Warra, Queensland, with fertilizers, no-tillage, or legumes 2. Long-term fertiliser nitrogen needs to enhance wheat yields and grain protein. *Australian Journal of Experimental Agriculture* **36**, 665-674.

TRYM: A simplified process model in use by the NSW rice industry

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Abstract

A simplified crop process model, called TRYM (Temperate Rice Yield Model), has been developed for use in the NSW rice industry. TRYM predicts rice growth and yield based on environmental conditions and grower management options. It was based on field experimentation with treatments which produced the full range of yields observed by farmers. A top-down analysis of yield and yield components defined the level of complexity of the crop model. TRYM has been widely used as part of a decision support system called maNAge rice.

Introduction

Growing rice in southern NSW can be a very risky occupation, with large yield variation across fields and seasons. Below-average temperatures during the reproductive stage can dramatically reduce rice yields. In the 1995/96 rice season, the average yield was reduced by 25% as a result of minimum air temperatures that were 4°C below average for 30 days during the critical reproductive stage. During that season, farmer yields ranged from 0 to 13 t/ha.

In response to the almost chaotic pattern of rice yields, a computer model of rice growth was developed, tested, evaluated and incorporated into a decision support system to help farmers manage their rice crops. The resulting model was named the Temperate Rice Yield Model (TRYM).

Experimental work

The initial aim of the rice modelling work was to mimic the variation in rice yield in a controlled replicated experiment, changing only the management factors available to rice growers. These factors included variety, N fertiliser application rate, sowing date, and water depth at early pollen microspore.

An initial experiment was established in 1991/92 at Deniliquin. This used a factorial combination of 3 varieties (Amaroo, Jarrah and Doongara), 4 pre-flood N rates (0, 75, 125 and 250 kgN/ha), 2 sowing dates (26 September and 31 October) and 2 water depths (5 and 20 cm) at early pollen microspore. Details of the trial are described in Williams and Angus (1994).

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Yield for Amaroo in this trial ranged from 0 to 12 t/ha. Total dry matter at maturity was little affected by sowing date and water depth, but increased from 16 to 22 t/ha with nitrogen application. Grain yield response to N fertiliser was dependent on sowing date, water depth and variety. For early-sown crops grown in deep water, yields increased from 7 to 13 t/ha with increased N supply. For early-sown crops grown in shallow water, yields declined from 7 to 3 t/ha with increasing N supply. For the later October sowing date, yields declined with applied N at both water depths.

Guiding principles for developing TRYM

A top-down approach was employed to explore the reasons for yield differences, and to develop the crop model. Yield components were broken down only until each component was adequately correlated with a management decision (such as N application rate or water depth) or an environmental variable (temperature or radiation). This process has the advantage of limiting the complexity of the resulting model, while ensuring sufficient complexity to describe the experimental field results. A second guiding principle is to only simulate characters that can be reasonably observed and measured. As a result of this constraint the model does not attempt to simulate processes such as crop respiration, or the size of different N pools. The third principle is to use a minimum of parameters to describe the yield variation.

Crop Model

Grain yield is described as a product of harvest index and above-ground biomass at maturity. Harvest index is simulated only once (at early microspore). It is assumed to be a genetically determined maximum value, unless panicle temperature at early microspore falls below a threshold, in which case the harvest index is reduced. The reduction is more dramatic for high N status crops. The growth component of the model has a daily time step, and simulates changes in N uptake, leaf area index, radiation interception and above-ground biomass. N uptake for each day is calculated as the product of the day's mean temperature and the rate of N uptake per unit temperature. Application of fertiliser N increases this rate, allowing the model to simulate the response to applied N. Leaf area index prior to flowering is estimated as a linear function of N uptake; after flowering, leaf area index is reduced by 1% per day. Radiation interception is estimated from the leaf area index according to Beer's law. Above-ground biomass is modelled as the product of intercepted solar radiation and a fixed radiation use efficiency.

Data requirements

Inputs required by TRYM are the variety, sowing date, flowering date, fertiliser application rates and dates, daily maximum and minimum temperatures and solar radiation, as well as one observation of N content during the crop cycle. TRYM is unable to simulate N uptake of a particular soil based on soil characteristics. To enable simulation of N content of the crop through the season, one observation is required to initialise the model. This data is used to calculate the previous soil mineralisation rate, which is then projected into the future. However, once the soil mineralisation rate is set, yield predictions for a range of N management options can be calculated.

Validation

TRYM was tested using a range of data sets over 3 years to determine whether the observed yield responses to N applied pre-flood and at panicle initiation were simulated correctly. In each case the simulation was initialised by the crop N content at panicle initiation. Sowing date, PI date and the nitrogen uptake of the crop at that time were used as inputs into the model, as were data on daily temperatures and solar radiation. The model simulated the daily change in leaf area, nitrogen uptake and biomass until maturity.

Table 1. Average observed and simulated rice yield with no PI applied N and with 75 kg N/ha applied for a range of PI N uptake values over a range of locations and 3 years.

Range of N uptake (kg N/ha)	Number of crops	Mean N uptake (kg N/ha)	Yield with no N at PI (t/ha)		Response to 75 kg N/ha at PI (t/ha)	
			Observed	Simulated	Observed	Simulated
15-40	11	26	6.1	5.8	1.6	2.1
40-70	15	51	8.5	8.2	1.5	1.3
70-100	6	84	10.3	9.5	1.0	0.8
100-130	11	112	11.7	11.3	0.4	0.5
130-180	10	155	11.6	11.8	-0.1	0.2

TRYM predicted the average observed yield for crops within particular ranges of N uptake with an average error (Root Mean Square Deviation) of 0.44 t/ha (Table 1). The model predicted grain yield of individual plots with an average error (Root Mean Square Deviation) of 0.95, 1.7 and 1.6 t/ha for the years 1995, 1996 and 1996 respectively. The error of observation of grain yield was just over 1.0 t/ha in each of the trials. The predicted yields show no bias in relation to the observed yields (Fig. 1).

TRYM also adequately predicted the yield response to the addition of 75 kgN/ha at panicle initiation for crops with a range of N uptake (Table 1) with an average error of 0.25 t/ha. Average error of predicted yield response for individual crops was 0.98, 0.93 and 1.2 for the years 1995, 1996 and 1997 respectively (Fig. 2).

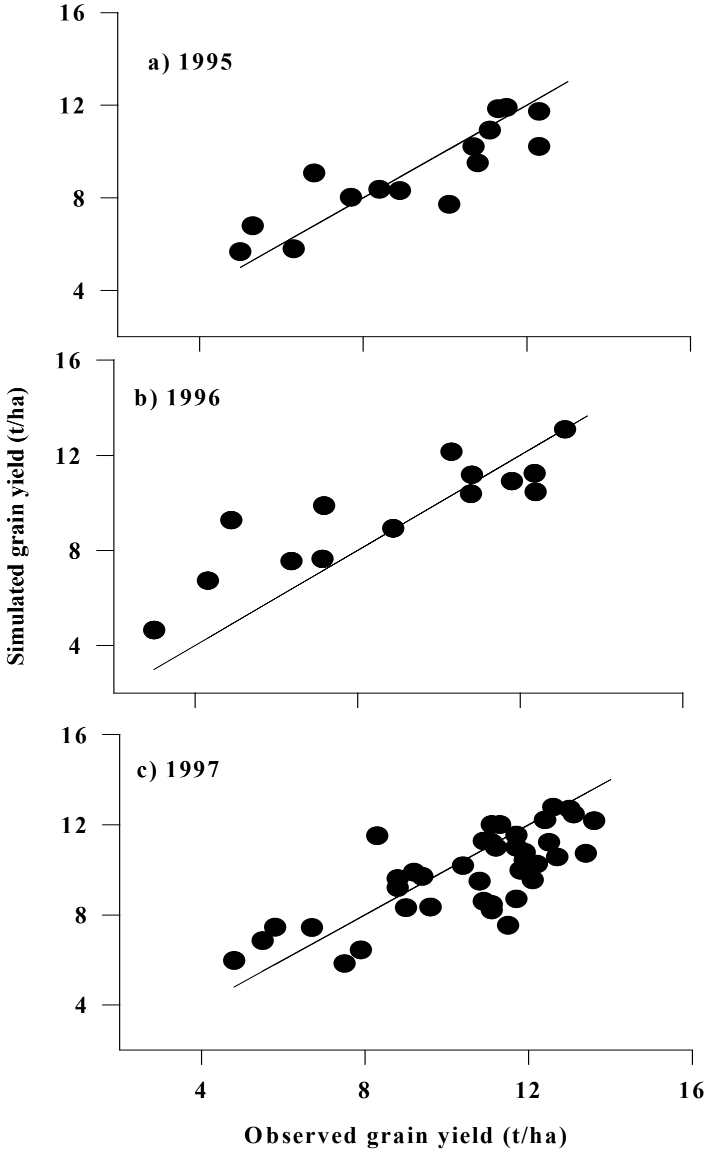

Figure 1. Predicted versus observed grain yield for a range of rice crops with no N applied after flooding.

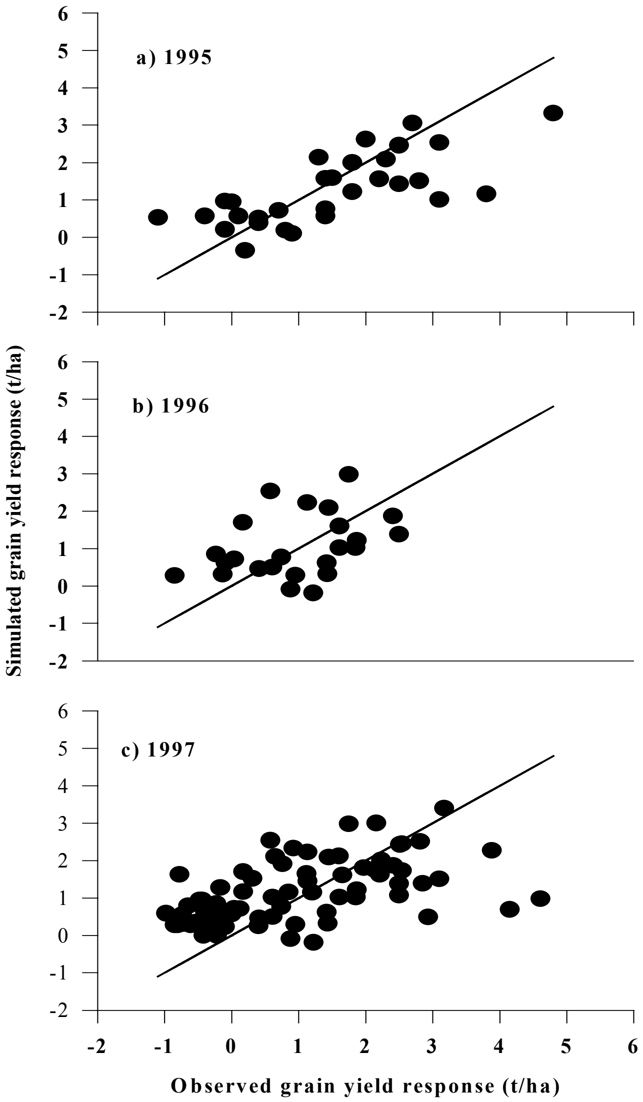

Figure 2. Predicted versus observed yield response to additional 75 kg N/ha applied at panicle initiation.

Application

TRYM has been used as the basis of the rice decision support system maNage rice. The software program **maNage rice** has been used by an increasing number of ricegrowers over the last 9 years. Currently more than 500 updates of the software are sent to growers annually. Growers use the software in 2 ways. The first is as a general educational tool, with the grower asking questions such as “Can I get 10 t/ha yield every year?”, “To do that what must I change?”, “What are the risks of cold damage if I follow the high N input option?”, “What are the economic consequences of following the high N input option?”, etc. The second way growers use **maNage rice** is to determine particular predictions for their crops. maNAge rice allows for the prediction of the dates of PI, flowering and maturity, as well as providing information on the costs and benefits of various PI top dressing rates.

References

Williams, R.L., Angus, J. (1994). Deep floodwater protects high-nitrogen rice crops from low temeprature damage. *Australian Journal of Experimental Agriculture* **34**:927-932.

A short description of the simulation model FUSSIM2 illustrated with two examples

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Model description

FUSSIM2 is a two-dimensional simulation model for describing water movement, solute transport and root uptake of water and nutrients in partially saturated porous media. It was documented by Heinen and de Willigen (1998). Since then there have been additions to FUSSIM2, which are described in a second report (Heinen and de Willigen, 2001). Figure 1 gives an overview of the processes included in FUSSIM2 proper, and the rectangular domain to which the model generally applies. Recently a related model FUSSIMR has been developed which deals with two-dimensional (radial and vertical) flow in a cylindrical geometry. Likewise FUSSIM2 has been extended to FUSSIM3, a three-dimensional model in Cartesian coordinates.

The new features include: extension to the van Genuchten-Mualem description of the physical properties of the porous medium, reduction of evaporation of water at the soil surface, runoff, the Vimoke drain concept, P-adsorption and P-fixation, non-zero sink nutrient uptake, root growth described as a diffusion process, nitrification and denitrification, soil temperature. Furthermore, a version in cylindrical coordinates is available, FUSSIM2 is coupled with the organic matter model MOTOR, and an expo-linear growth and demand module is included in FUSSIM2 for special situations.

Figure 2 shows the various components of which Fussim2 consists. The core of the model is the routine that calculates the flow of water, and the distribution of pressure head and water content. It numerically solves Richard's equation together with initial and boundary conditions (Fig. 3). The calculation of solute transport is shown in Fig. 4. The governing equation is that of convection and dispersion. The calculation of the uptake rate both of water and solutes is based on analytical solutions derived by de Willigen and van Noordwijk (1987, 1994 a and b). Root growth is described as a diffusion process with a first order decay rate (Fig. 5).

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FUSSIM2

- A **two-dimensional** simulation model for
  - **water movement**
  - **solute transport**
  - **root water uptake**
  - **root nutrient uptake**
  - **root length density distribution**

  in **unsaturated-saturated porous media**

- Also available
  - FUSSIMR
  - FUSSIM3

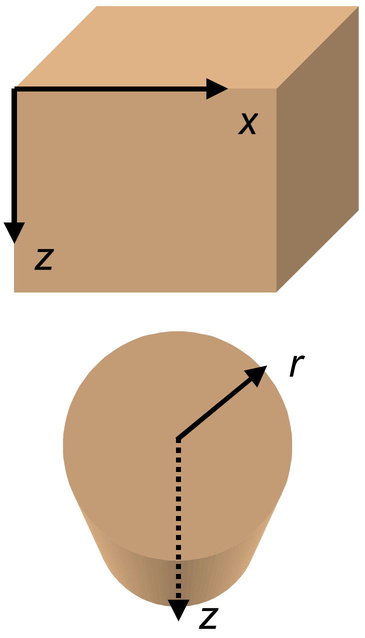
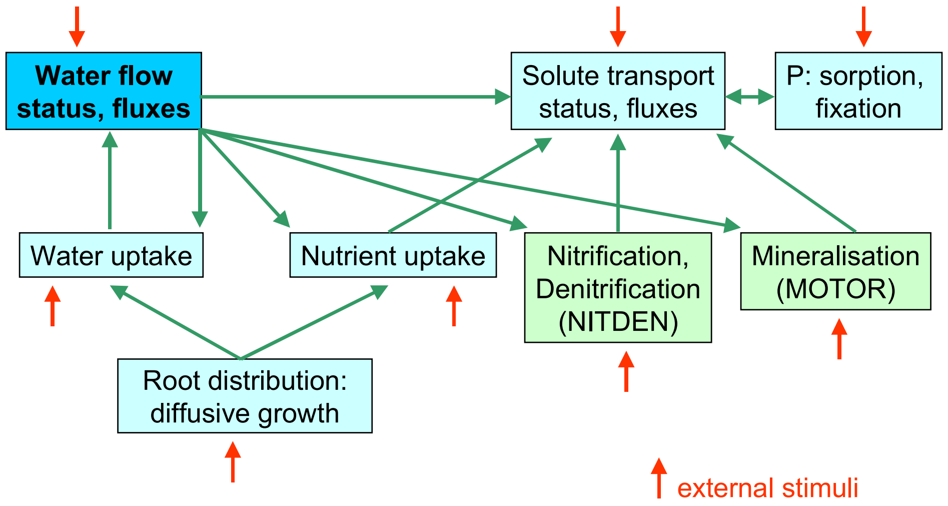


Figure 1. Overview of processes included in FUSSIM2 and the type of domains the model deals with.

FUSSIM2: components


Water flow status, fluxes

Solute transport status, fluxes

P: sorption, fixation

Water uptake

Nutrient uptake

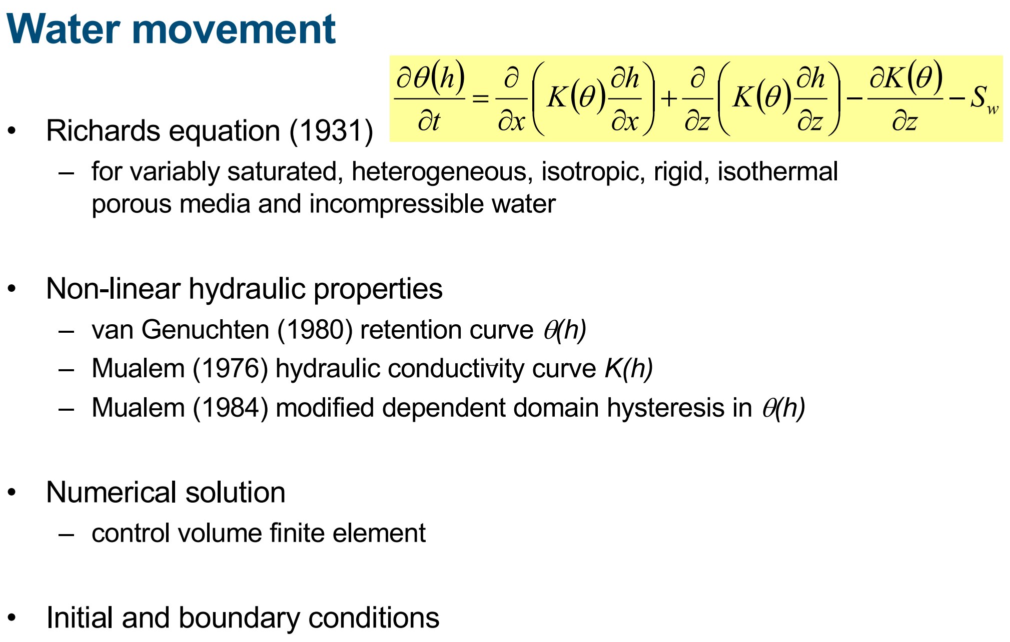
Nitrification, Denitrification (NITDEN)

Mineralisation (MOTOR)

Root distribution: diffusive growth

external stimuli

Figure 2. The interaction between the various components of FUSSIM2.



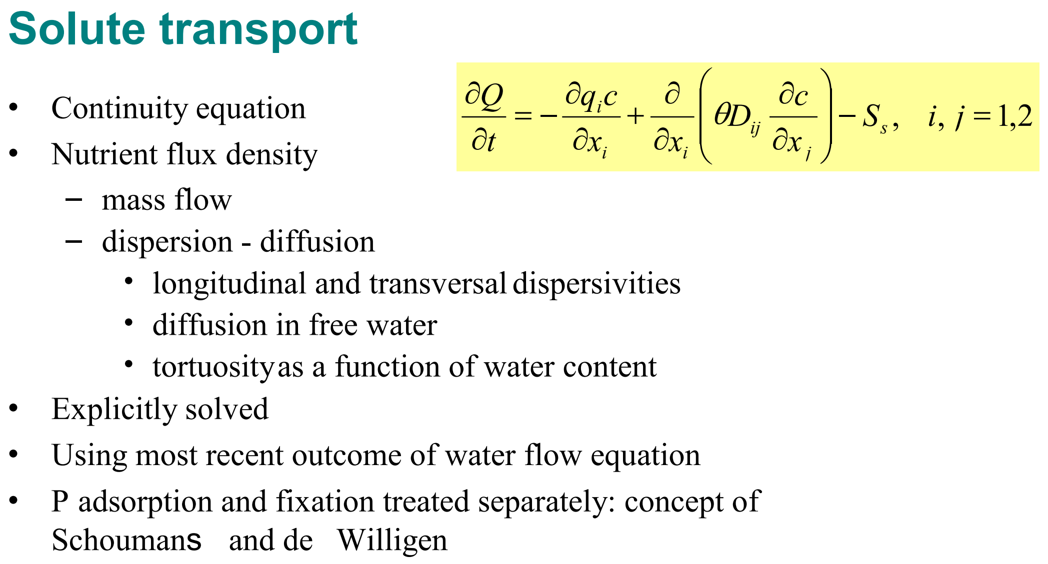
Water movement

- Richards equation (1931)

$$\frac{\partial\theta(h)}{\partial t}=\frac{\partial}{\partial x}\left(K(\theta)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(K(\theta)\frac{\partial h}{\partial z}\right)-\frac{\partial K(\theta)}{\partial z}-S_w$$

  - for variably saturated, heterogeneous, isotropic, rigid, isothermal porous media and incompressible water
- Non-linear hydraulic properties
  - van Genuchten (1980) retention curve *θ(h)*
  - Mualem (1976) hydraulic conductivity curve *K(h)*
  - Mualem (1984) modified dependent domain hysteresis in *θ(h)*
- Numerical solution
  - control volume finite element
- Initial and boundary conditions

Figure 3. Scheme of calculation of watertransport, based on Richard's equation with a sink term (S_w) accounting for water uptake by the plant.



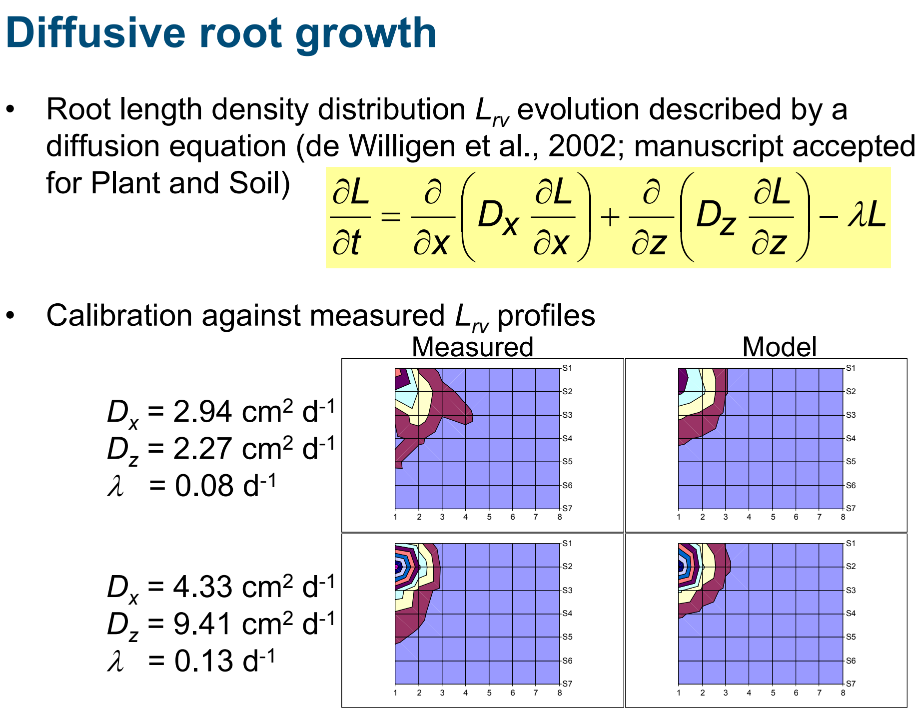
Solute transport

- Continuity equation
- Nutrient flux density

$$\frac{\partial Q}{\partial t}=-\frac{\partial q_i c}{\partial x_i}+\frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right)-S_s,\quad i,j=1,2$$

  - mass flow
  - dispersion - diffusion
    - longitudinal and transversal dispersivities
    - diffusion in free water
    - tortuosityas a function of water content
- Explicitly solved
- Using most recent outcome of water flow equation
- P adsorption and fixation treated separately: concept of Schoumans and de Willigen

Figure 4. As for figure 3 for solute transport.



Diffusive root growth

- Root length density distribution L_{rv} evolution described by a diffusion equation (de Willigen et al., 2002; manuscript accepted for Plant and Soil)

$$\frac{\partial L}{\partial t} = \frac{\partial}{\partial x}\left(D_X \frac{\partial L}{\partial x}\right) + \frac{\partial}{\partial z}\left(D_Z \frac{\partial L}{\partial z}\right) - \lambda L$$

- Calibration against measured L_{rv} profiles

$D_x = 2.94\ \mathrm{cm^2\ d^{-1}}$
$D_z = 2.27\ \mathrm{cm^2\ d^{-1}}$
$\lambda\ = 0.08\ \mathrm{d^{-1}}$

$D_x = 4.33\ \mathrm{cm^2\ d^{-1}}$
$D_z = 9.41\ \mathrm{cm^2\ d^{-1}}$
$\lambda\ = 0.13\ \mathrm{d^{-1}}$

Figure 5. Root growth calculation in FUSSIM2. It is described as a diffusion process together with a first-order decay rate.

Examples

1. Uptake of water by lettuce grown on a sandbed

Figure 6 shows the results of a validation study by Heinen (1997). These pertain to lettuce grown on a sandbed. Water was applied through trickle irrigation. The figure shows good agreement between observed and calculated values of the water content, especially when hysteresis in the moisture retention curve is taken into account.

2. Pressure head distribution in a potato ridge

Figure 7 depicts the pressure head distribution under a potato plant grown in a ridge. (de Vos and Heinen, 1998) Again a fair agreement between observed and calculated values is obtained.

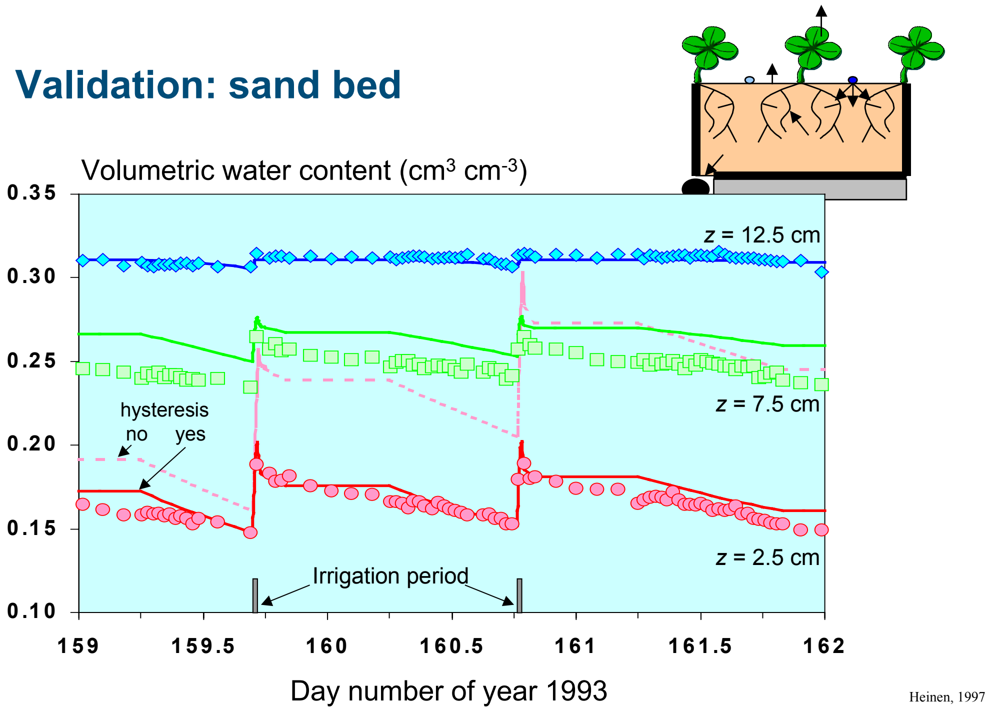


Figure 6. Calculated and observed time course of water content at different depths in a sandbed under lettuce.

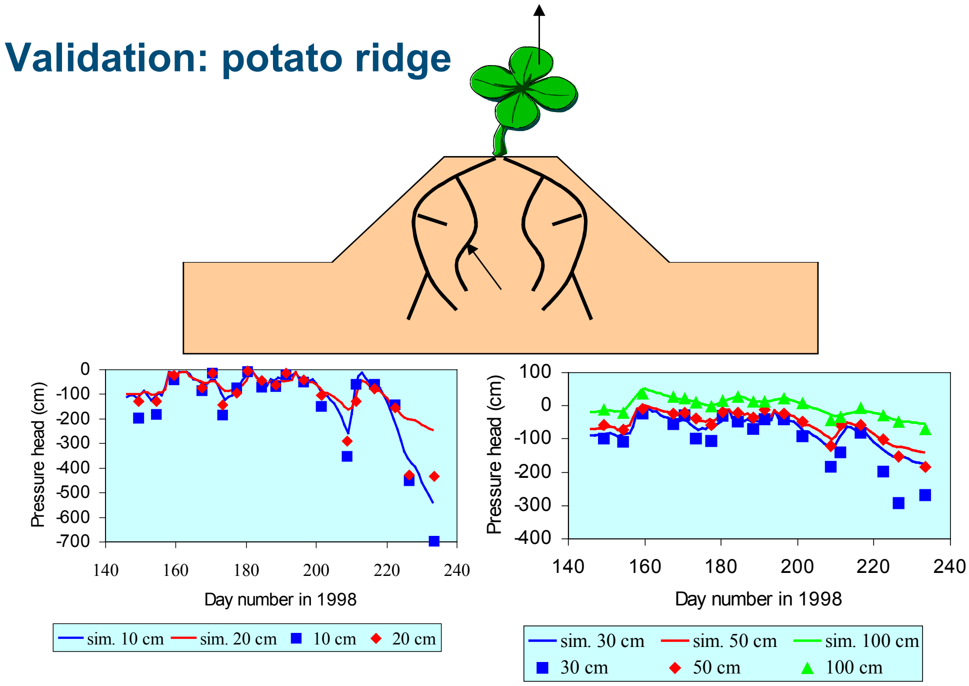


Figure 7. Validation for potato ridge

Listing of most important inputs for calibration and validation

- General (spatial and temporal discretisation; initial and boundary conditions)
- Water movement (rain, water demand by crop, evaporation demand, hydraulic properties)
- Nutrient transport (longitudinal and transversal dispersivities, tortuosity parameters, P adsorption and fixation parameters, nutrient demand, fertilization)
- Water uptake, WU (transpiration reduction function, osmotic parameters in WU model)
- Nutrient uptake, NU (physiological maximum NU rate, minimum concentraion at root surface at which NU can occur)
- Root diffusive growth (diffusion coefficients and specific decay rate, root radius, root fresh density, root dry matter content)

References

De Vos JA, Heinen, M (1999). Synchronization of application of manure with spatial and temporal variation. (*In Dutch)*. Alterra-rapport 110, 44 pp.

De Willigen P, van Noordwijk, DM (1987). Roots, plant production and nutrient use efficiency. PhD Thesis, Agricultural University, Wageningen, The Netherlands, 282 pp.

De Willigen P, van Noordwijk, DM (1994a). Mass flow and diffusion of nutrients to a root with constant or zero-sink uptake. I. Constant uptake. *Soil Science* **157**: 162-170.

De Willigen P, van Noordwijk, DM (1994b). Mass flow and diffusion of nutrients to a root with constant or zero-sink uptake. I. Zero-sink uptake. *Soil Science* **157**: 171-175.

Heinen M (1997). Dynamics of water and nutrients in closed, recirculating cropping systems in glasshouse horticulture. PhD Thesis, Agricultural University, Wageningen, The Netherlands, 270 pp.

Heinen M., de Willigen, P (1998). FUSSIM2. A two-dimensional simulation model for water flow, slute transport, and root uptake of water and nutrients in partly unsaturated porous media. Quantitative Approaches in Systems Analysis No. 20, AB-DLO and PE, Wageningen, The Netherlands, 140 pp.

Heinen M, de Willigen, P (2001). FUSSIM2 version 5. New features and updated user’s guide. Alterra-rapport 363, 164 pp

Potential for application of HYDRUS-2D to analysis of water flow and solute transport of bed layouts in irrigated cropping systems

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Model description

Hydrus-2D is a windows based computer package capable of simulating water, heat and multiple solutes movement in 2-D variably saturated (unsaturated, partially saturated, or fully saturated) media. The model was developed by scientists and students at U.S. Salinity Laboratory, Agricultural Research Station, Riverside, California. Rien van Genuchten and Jirka Simunek are the lead authors of the computer program.

Description of the model (version 2.0), its validation, and details of input data requirements and output files generated are well-documented (Simunek et al. 1999). Here, only a summary of model and the input data requirements are presented.

Hydrus-2D numerically solves Richards' equation for saturated-unsaturated water flow and the convection-dispersion for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. The heat transport equation considers transport due to conduction and convection with flowing water. The solute transport equations consider convective-dispersive transport in the liquid phase, as well as diffusion in the gaseous phase.

The model can handle flow regions delineated by irregular boundaries, and the flow and transport can occur in the vertical and horizontal planes, or in a 3-D region exhibiting radial symmetry about the vertical axis. The water flow part of the model can deal with prescribed head and flux boundaries, boundaries controlled by atmospheric conditions, free drainage boundary conditions, as well as simplified representation of nodal drains using results of electric analog experiments. A mesh generator that is incorporated in the package generates unstructured finite element mesh for any domain and there are provisions for specifying water flow boundaries in addition to flux drainage and seepage faces. These pre-processing tools provide easy characterization of any flow domain and are well suited for domains with irregular boundaries.

Discretization of the flow domain into triangular or rectangular regions enables water contents and pressure heads to be determined along the soil profile at the middle and edges of bed that provides information about the redox potential and consequent effects on organic matter decay, N transformations and proliferation of plant roots. Velocity profiles provide information about preferential water flow paths and possible soil erosion and disintegration of bed geometry. The

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solute transport component provides information about the migration of salts and possible migration towards the top center of the bed. The flow equations incorporate a sink term (Feddes et. al. 1978) to account for water uptake by plant roots.

Data requirements

There are seven input data files, which consist of one or more input blocks identified by the letters from A through M. The input files and blocks are:

- SELECTOR.IN (A - Basic information; B – Material information; C – Time information; D – Root water uptake information; E – Solute transport information; F – Heat transport information)
- MESHTRIA.TXT (G. Finite element mesh information)
- DOMAIN.DAT (H – Nodal information; I – Element information)
- BOUNDARY.IN (J – Boundary information)
- ATMOSPH.IN (K – Atmospheric information)
- DIMENSIO.IN (L – Dimension information)
- FIT.IN (M – Inverse solution information)

Basic information consists of data detailing units (length, time, and mass), type of flow (horizontal, vertical, or axis-symmetric flow), number of iterations used, absolute water content tolerance for nodes in the unsaturated part of the flow region, absolute pressure head tolerance for nodes in the saturated part of the flow region, and setting up various logical variables either TRUE or FALSE depending upon the conditions used in simulation. **Material information** includes the number of soil materials and subregions, absolute values of the upper and lower limits of the pressure head interval, soil hydraulic properties model being used (i.e. van Genuchten, Vogel and Cislerova, or Brooks and Corey), hysteresis, and van Genuchten parameters (θ_s, θ_r, α, n, m, K_s) specified for each soil type. **Time information** includes initial and maximum time increments and initial and final time of the simulation, etc. **Root water uptake information** includes pressure heads, potential transpiration rates required for root water uptake stress function using either Feddes et al. 1978 or van Genuchten 1987, and parameters thresholds for reducing the water uptake due to salinity. Solute and heat transport related data are required only if their respective logical variables are set to TRUE.

Finite element mesh information includes data on the number of nodes, nodal points, mesh edges, finite elements, and beginning and end nodes of edge. Nodal information consists of data such as initial values of pressure head and prescribed recharge/discharge rate at node ‘n’, value of the water uptake distribution in the root zone at node ‘n’, nodal values of the dimensionless scaling factors associated with the pressure head, saturated hydraulic conductivity, and water content, and initial values of temperature, solute concentrations, and adsorbed concentrations based on whether logical variables for solutes and temperatures are set to either TRUE or FALSE. Element information consists of data on element number, angle, and first and second principal components.

Boundary information includes data on number of boundary and observation nodes, setting up logical variables to TRUE or FALSE depending on seepage faces, hydraulic gradient boundary, drain simulation, and discharge-groundwater relationship, global node numbers for various boundary nodes, width of the boundary associated with the boundary node, reference position of the groundwater, number of seepage faces and number of nodes on various seepage faces, sequential global numbers of various nodes on the first seepage face, number of drains and global numbers of various drains, number of elements surrounding various drains, global numbers of various elements surrounding the first drain, and codes specifying the type of boundary condition for solute and heat transport applied to various boundary nodes if logical variables for each of solute or heat transport are set to TRUE.

Atmospheric information includes data such as minimum and maximum allowed pressure head at the soil surface, precipitation, potential evaporation and transpiration rates, drainage flux across the bottom boundary and groundwater level, and first and second time-dependent temperatures and first, second, and third time-dependent solute concentrations for various nodes depending upon whether logical variables for each of solute or heat transport are set to TRUE or FALSE.

Dimension information consists of data on the maximum number of nodes and elements in the finite element mesh, and maximum number of boundary nodes, seepage faces, nodes along a seepage face, drains, elements surrounding one drain, materials, observation nodes, and solutes in a chain reaction.

Inverse solution information is not required if only the direct solution is calculated.

Output files: The program output consists of several output files, organized into 3 groups (T-level, P-level, and A-level information). Graphical display of results includes pressure heads, water content, velocity, solute concentrations, and temperature.

Model testing and applications

Hydrus-2D allows for the design of irrigation systems that provide optimal water to crops while mitigating the pollution of groundwater resource from leached fertilizers and pesticides. It is a tool that is ideally suited for preliminary investigations into the water, salt and nitrogen balance of bed layouts. The model has been applied in both agricultural and non-agricultural sectors. The agricultural-related applications include: irrigation management, drip and sprinkler irrigation and tile drainage designs, salinization and reclamation processes, leaching of salt and movement of pesticides and non-point source pollution, seasonal simulation of water flow and plant response, and crop (e.g. cotton) growth modeling.

HYDRUS-2D has been validated and tested for a range of situations across the world. For example, Simunek et al. (1998a) used HYDRUS-2D to analyse the soil hydraulic properties data estimated from the numerical inversion of the Richards' equation using tension disc permeameter, modified cone penetrometer, and a multiple-step field extraction device in USA. They (Simunek et al. 1998b) also did parameter estimation analyses of the evaporation method for determining soil hydraulic properties using the model, also in USA. The model is also being used in simulation of Cl profiles in soil and in understanding the origin and dynamics of Cl concentrations in the drainage water and the salinisation process, resulting from upward movement of Cl from the subsoil and from additions of fertilizer in surface soil, in a polder in the Netherlands (Vos et al. 2002) and in simulation of pesticide (picloram, atrazine, and simazine) leaching through soils and into groundwater in New Zealand (Liping et al. 2000). In the latter study, the model provided a reasonable link for pesticide transport in both the unsaturated zone and groundwater, and both observed and simulated bromide and pesticide concentrations indicated that solutes leached more quickly through the soils that were coarser and more heterogeneous, but were more diluted in the groundwater system that was more heterogeneous, conductive, and dispersive. Mailhol et al. (2001) used HYDRUS-2D to assess the interpretations of yield and nitrate leaching data and strengthen the conclusions derived from the observations from two irrigation and fertilization strategies under furrow irrigation in south-east France. The model helped illustrate the risk of over-estimation of N leaching when using a simplified 1D solute-transport model. Also in France, Chabot et al. (2002) compared calculated soil water flows from pressure head measurements with predicted pressure heads by the HYDRUS-2D, and predicted the root water uptake patterns of sugarcane under a lysimeter. Rassam and Cook (2001) used the HYDRUS-2D to simulate the transport of SO_4^{--} ions through the soils and through drainage water in an acid-sulfate soil on a coastal plain in southeast Queensland in Australia. Results of the field-scale inverse modeling showed that the hydraulic conductivity was two orders of magnitude higher than the field measurement using the auger hole method. Adopting the physical non-equilibrium model resulted in predictions of cumulative SO_4^{--} ions, which were closest to those observed in the field.

The model continues to evolve due to cooperative research and development agreement with Colorado school of mines international groundwater modeling center (IGWMC) in Golden, Colorado. IGWMC distributes the model, provides help to users and runs short courses.

Conclusions

There is a great potential for using HYDRS-2D in simulating the water and nutrients flow under bed and furrow system of growing crops under irrigation situation.

References

Chabot R, Bouarfa S, Zimmer D, Chaumont C, Duprez C (2002). Sugarcane transpiration with shallow water-table: sap flow measurements and modeling. *Agricultural Water Management* **54**, 17-36.

De Vos JA, Raata, PAC Feddes, RA (2002). Chloride transport in a recently reclaimed Dutch polder. *Journal of Hydrology* **257**, 59-77.

Feddes RJ, Kowalik PJ, Zaradny H (1978). Simulation of field water use and crop yield. Simulation Monographs 188 p. Pudoc, Wageningen, Netherlands.

Mailhol JC, Ruelle P, Nemeth I (2001). Impact of fertilization practices on nitrogen leaching under irrigation. *Irrigation Science* **20**, 139-147.

Pang L, Close ME, Watt PC, Vincent KW (2000). Simulation of picloram, atrazine, and simazine leaching through two New Zealand soils and into groundwater using HYDRUS-2D. *Journal of Contaminant Hydrology* **44**, 19-46.

Rassam DW, Cook FJ (2001). Modelling the transport of SO_4^{--} ions in acid sulfate soils. In: Ghassemi, F., Post, D., Sivapalan, M., Vertessy, R. (Eds.), MODSIM 2001 International Congress on Modeling and Simulation. 1. Natural Systems (Part one). Modeling and Simulation Society of Australia and New Zealand Inc., ANU, Canberra, Australia.

Simunek J, Sejina M, van Genuchten M Th (1999). The HYDRUS-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably-saturated media, version 2.0, U.S. Salinity Laboratory, USDA, ARS, Riverside, California. 227 pp.

Simunek J, van Genuchten M Th, Gribb MM, Hopmans JW (1998a). Parameter estimation of unsaturated soil hydraulic properties from transient flow processes. *Soil and Tillage Research* **47**, 27-36.

Simunek J, Wendroth O, van Genuchten M Th (1998b). Parameter estimation analyses of the evaporation method for determining soil hydraulic properties. *Soil Science Society of America Journal* **62**, 894-905.

Application of SWAGMAN® Destiny to rice-wheat cropping systems

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Introduction

A decline in productivity as a result of resource degradation has become apparent in many irrigated areas of the world (Ghassemi *et al*. 1995). This decline is often associated with watertable rise and the onset of problems of waterlogging and secondary soil salinisation. Salinisation is the process leading to an increase in the concentration of soluble salts within the rootzone of the soil. Secondary salinisation is the result of the salt stored in the soil profile and/or groundwater being mobilized by extra water provided by human activities such as irrigation or land clearing. In addition, salts continue to be added through irrigation water and rainfall. Salinisation arises due to rising watertables, which enhance capillary upflow of groundwater to the root zone. As the groundwater is evaporated (via crops or direct from the soil surface), the salt that was in the water accumulates in the soil. Both the increase in concentration of salt in the root zone and waterlogging affect the growth and development of crops and hence impact on yield and farmer income.

There are many interacting factors which determine the position of a watertable in a soil profile and its consequences for salinisation. Among the important factors are the underlying piezometric pressures, soil properties, weather, and crop and soil management. Simulation models which are able to capture the effects of these and other factors provide scope for the development of appropriate management scenarios for irrigated land.

In the rice cropping areas of south eastern Australia, watertable rise has occurred over the last few decades as a result of the underlying hydrological conditions, irrigation and clearing of perennial vegetation. Much of the area is at risk of salinisation, with shallow saline watertables already present over extensive areas. With large additions of water to the soil profile during the irrigation season, and particularly in the case of ponded rice, watertables rise. In some cases, this shallow groundwater can provide a valuable water resource for crops following rice (Humphreys *et al*. 2001). Models have a valuable role here in determining rates of watertable rise and salinisation, and in ascertaining responses to salinity. Appropriately constructed models can also be used to explore ways of utilizing shallow groundwater for crops following rice.

While low salinity (<0.2 dS/m) river water is the main source of irrigation water in the rice growing regions of Australia, groundwater is also a very important source in several regions. The

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salinity of the groundwater varies, and shandying with river water is practised in some locations. The number of on-farm recycling systems is also rapidly increasing leading to less export of salt off-farm and irrigation with water of higher salinity. Models have an important role to play in assessing the short and long term impacts of irrigating with water of varying salinities, and identifying management options for preventing accumulation of salt in the rootzone while maintaining productivity.

Shallow saline watertables and irrigation with water of varying salinities are also issues for significant parts of the Indo-Gangetic Plains (IGP), where rice-wheat systems are practiced on about 13 Mha and provide food for more than 1 billion people. In other parts of the IGP the hydrological conditions are very different. For example in Punjab, India, much of the irrigation water is sourced from shallow tube wells and as cropping intensity and pumping have increased, groundwater levels have fallen rapidly. Falling groundwater levels in this instance lead to increased pumping costs and may lead to water shortages. On the extensive areas of light-textured soils deep drainage is considerable and water is in almost constant re-use. Since there is continuous leaching of soil profiles, there inevitably will be accumulation of salts in the groundwater. Models are needed here to examine rates of salt leaching, salt accumulation in soil profiles and salt additions to groundwater, and the consequences of these for crop growth.

The SWAGMAN® Destiny model could be a particularly useful tool for identification of sustainable management options in those areas of IGP and in rice-based cropping systems of Australia where salinization and shallow water tables are increasingly becoming a concern. This paper provides a brief overview of SWAGMAN® Destiny, followed by examples of applications in rice-wheat systems in Bangladesh and Australia.

Description of SWAGMAN® Destiny

Overview

SWAGMAN® Destiny is a decision support tool developed to assist in the design and management of the soil/plant/atmosphere system. It enables strategies to be formulated that maximise productivity while minimising environmental degradation (salinisation). This is achieved in the model by simulating crop growth and yield in response to watertable levels, root zone salinity, available soil water, waterlogging and prevailing weather conditions. With long term weather data, different sequences of simulations can be used to assess a particular strategy by probabilistic analysis.

Crop growth

The canopy of an annual crop is provided with duration of growth specified by an accumulated thermal time. As the canopy develops, intercepted radiation is converted into biomass using an energy to mass conversion factor defined for the crop species. During the period of growth, biomass is apportioned to roots and distributed within the root zone according to a dynamic set of rules that determine the layers most favourable for root growth. Stresses due to water shortage, aeration, salinity and nitrogen are used to limit the growth processes and enhance senescence. For annual grain and fibre crops, yield is determined from a potential yield, and the rate at which simulated dry matter is reduced by prevailing stresses. Zero-to-unity stress indices are calculated during each day of simulation for soil water, salt, nitrogen and soil aeration (waterlogging). The most limiting of these stress indices is used to scale each day's potential growth.

Water and salt balance

The water balance component of SWAGMAN® Destiny is based on the SALUS model of Ritchie (1999 unpublished). Additional variations of the SALUS water balance now occur in the most recent versions of the CERES models. The water balance model simulates infiltration of water with provision for accumulation of ponded water on the surface, drainage from the profile, surface runoff, uptake of water by the crop, evaporation from the soil surface, and upward movement of water associated with evaporation.

The model uses a daily time step and simulates the prevailing water balance for a point in the landscape usually to the depth of rooting. Alterations to the SALUS model in SWAGMAN® Destiny involve the addition of procedures to describe the interaction with deeper groundwater. To accomplish this water balance calculations are performed over a 5 m depth of soil from the surface. In addition to this, piezometric pressure heads and fluxes at a plane 5 m deep are used as inputs to the model. Depending upon these pressures and the position of a watertable, water can either enter or leave the soil profile through the bottom boundary.

SWAGMAN® Destiny also simulates the balance of salt over a 5 m depth of soil from the surface. Salt additions from irrigation water and from saline groundwater entering the profile are simulated. Salt losses from the profile due to salt in surface runoff, deep drainage or sub-surface drainage are also simulated. Salt concentrations in each soil layer are updated daily and the consequences of this for root distribution and crop growth are determined. Detailed descriptions of the model can be found in (Godwin *et al*. 2002).

Model Validation

SWAGMAN® Destiny has been evaluated in a range of conditions. Weighing lysimeter experiments conducted by Meyer and co-workers (Meyer 1988; Meyer *et al.* 1990; Smith *et al.* 1993, 1996), with careful observations of evapotranspiration (ET) from crops grown with or without shallow watertables, formed the basis of early testing. Comparison of simulations with observations on ET, crop leaf area, root length density, volumetric water content, crop biomass and grain yield showed good agreement for crops of maize, wheat, soybean and lucerne. Additional field experiments on irrigated pastures overlying shallow saline watertables (Meyer *et al*. 1995) and data from perennial horticultural crops (peaches, vines) irrigated with saline water from several locations in Victoria have also been used to test the model (Boland *et al.* 1997) and apply it to evaluate lands throughout Victoria previously not used for growing horticultural crops **(**Agricultural Victoria 1999**)**. Additional validation of the groundwater simulation has come from observations tracking the watertables on a dryland pasture site in central Victoria. Details of other validation studies are presented in Xevi *et al*. (2002).

More recently, SWAGMAN® Destiny was validated against the performance of wheat growing in lysimeters and fields in the rice growing areas of south eastern Australia. Both the CERES Wheat and SWAGMAN® Destiny models were calibrated for three wheat varieties – Bindawarra, Janz and Yecora, and validated for a range of crop and soil parameters against independent data sets. Agreement between predicted and observed values was generally very good (Table 1, Figures 1-6).

Table 1 shows excellent agreement for predicted and observed yields, except for "Late 98" with SWAGMAN® Destiny. In this case the observed yield was 3.4 t/ha compared to the simulated yield of 1.9 t/ha. This discrepancy may be due to the external effect of a rise in the regional watertable observed when an adjacent paddock was flooded for rice (25th Sept), which the model did not know about. Consistent with this, the model simulated the soil profile a lot drier than it really was during October and November, which resulted in the lower yield prediction.

Table 1. Observed and predicted grain yields for irrigated wheat in south east Australia

Soil type	**Data set identity**	**Grain yield (t/ha) (dry)** **Obs.**	**CERES**	**Destiny**	**Cultivar**
Yooroobla Clay (Cal)	Coly93	4.0	3.9	4.0	Janz
Beelbangara Clay Loam (Ind)	Early98	4.2	4.2	4.1	Janz
Beelbangara Clay Loam (Ind)	Late98	3.4	3.3	1.9	Janz
Mundiwa Clay Loam(Cal)	L287	5.5	5.5	5.4	Yecora
Hanwood Loam (Ind)	L186	5.9	5.7	5.7	Yecora
Mundiwa Clay Loam (Cal)	Whit85	4.4	4.3	4.4	Bindawarra

Cal or Ind – Calibration or independent data set
L186 and L287 were studies in weighing lysimeters, all other studies were in field experiments
Coly 93, Early 98 and Late 98 were sown after rice

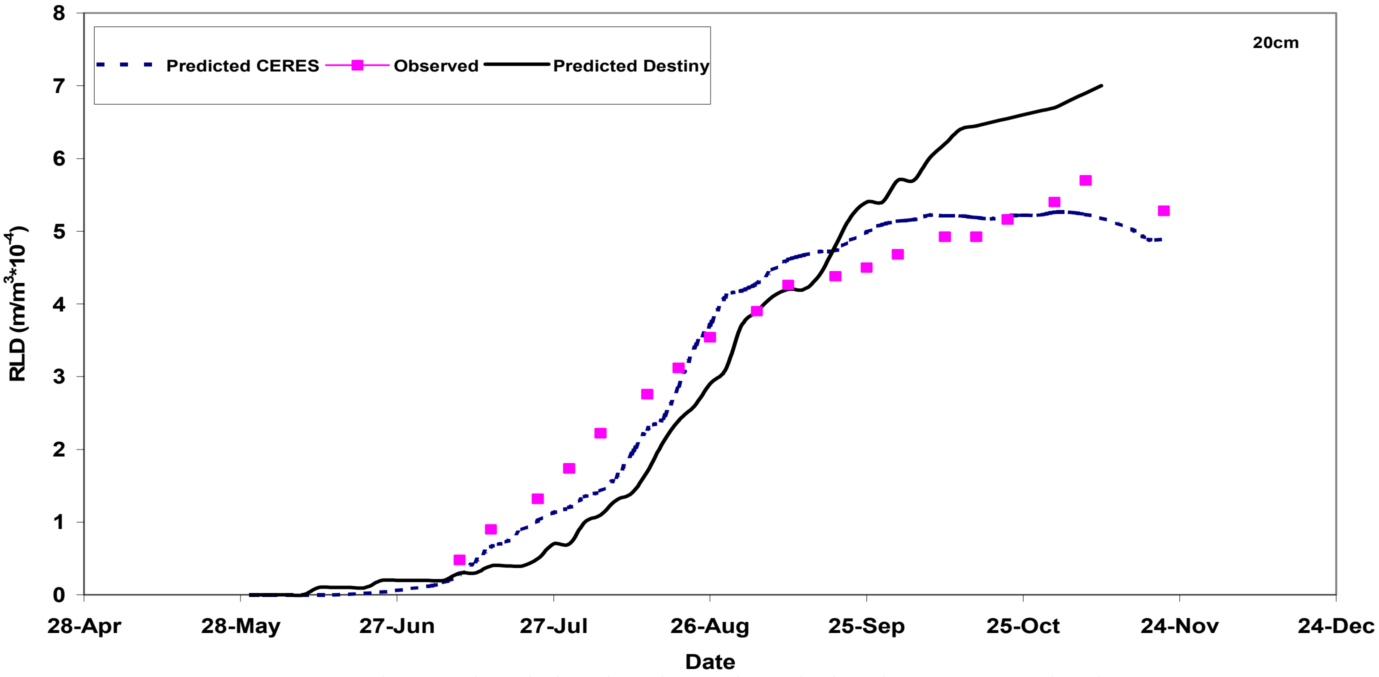

Figure 1. Observed and simulated root length density at 20 cm depth (L186).

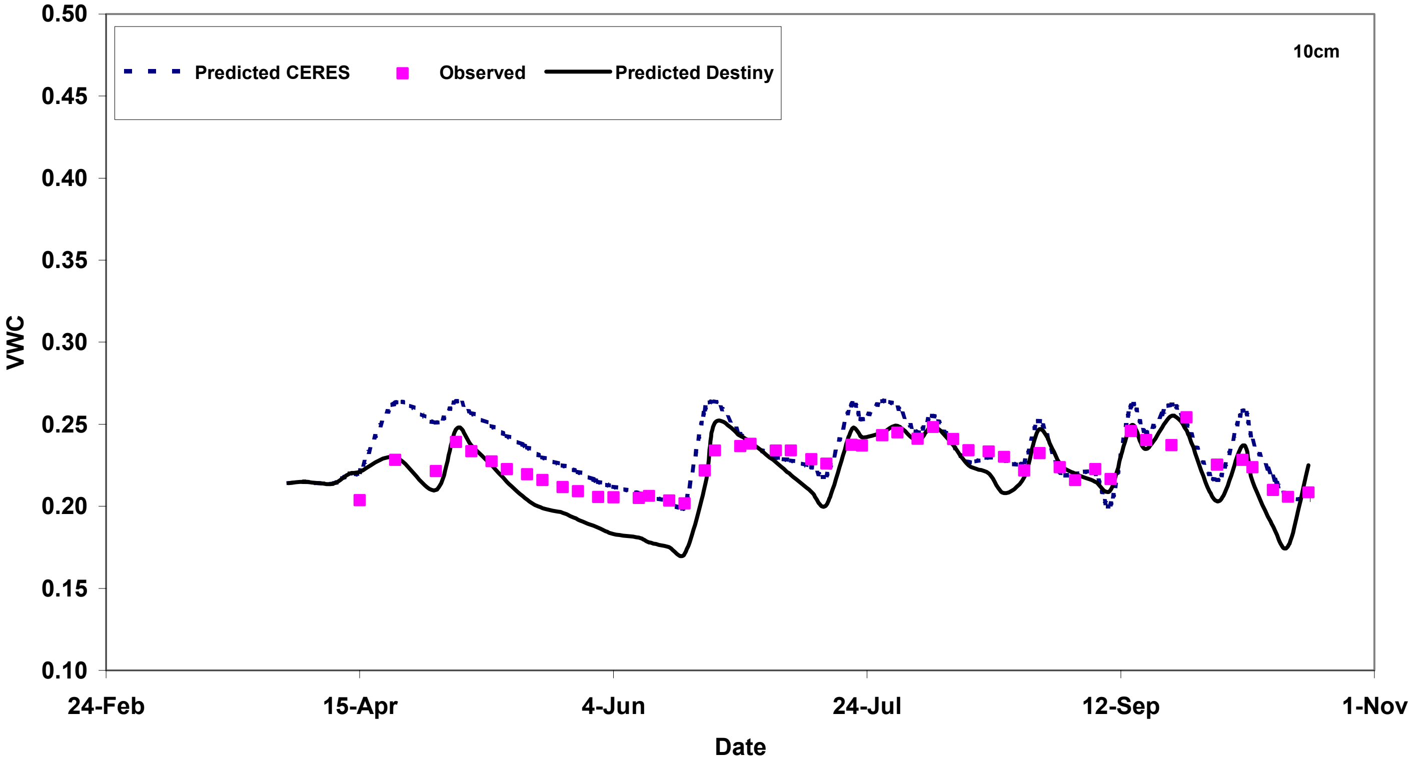

Figure 2. Observed and simulated soil volumetric water content at 10 cm depth (Early 98).

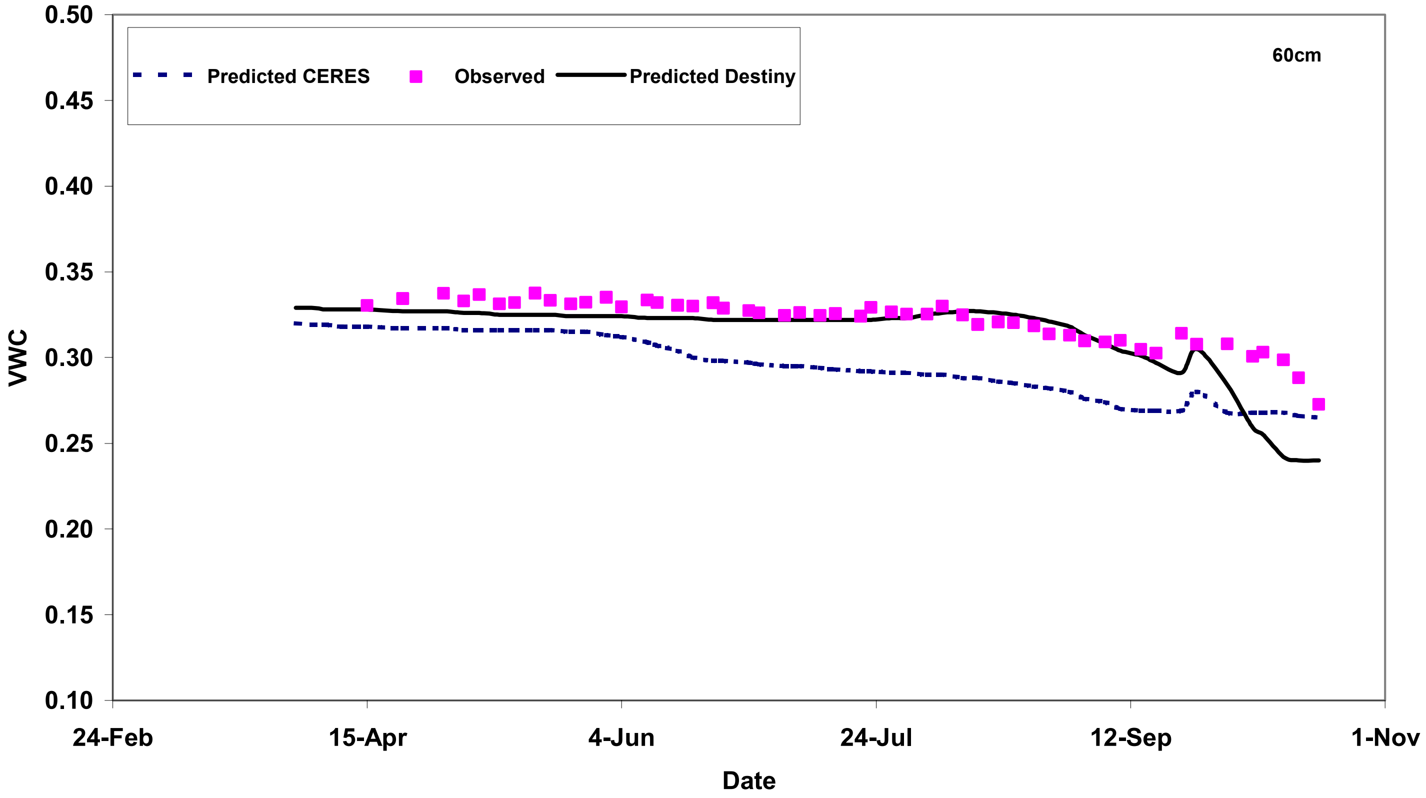

Figure 3. Observed and simulated soil volumetric water content at 60 cm depth (Early 98).

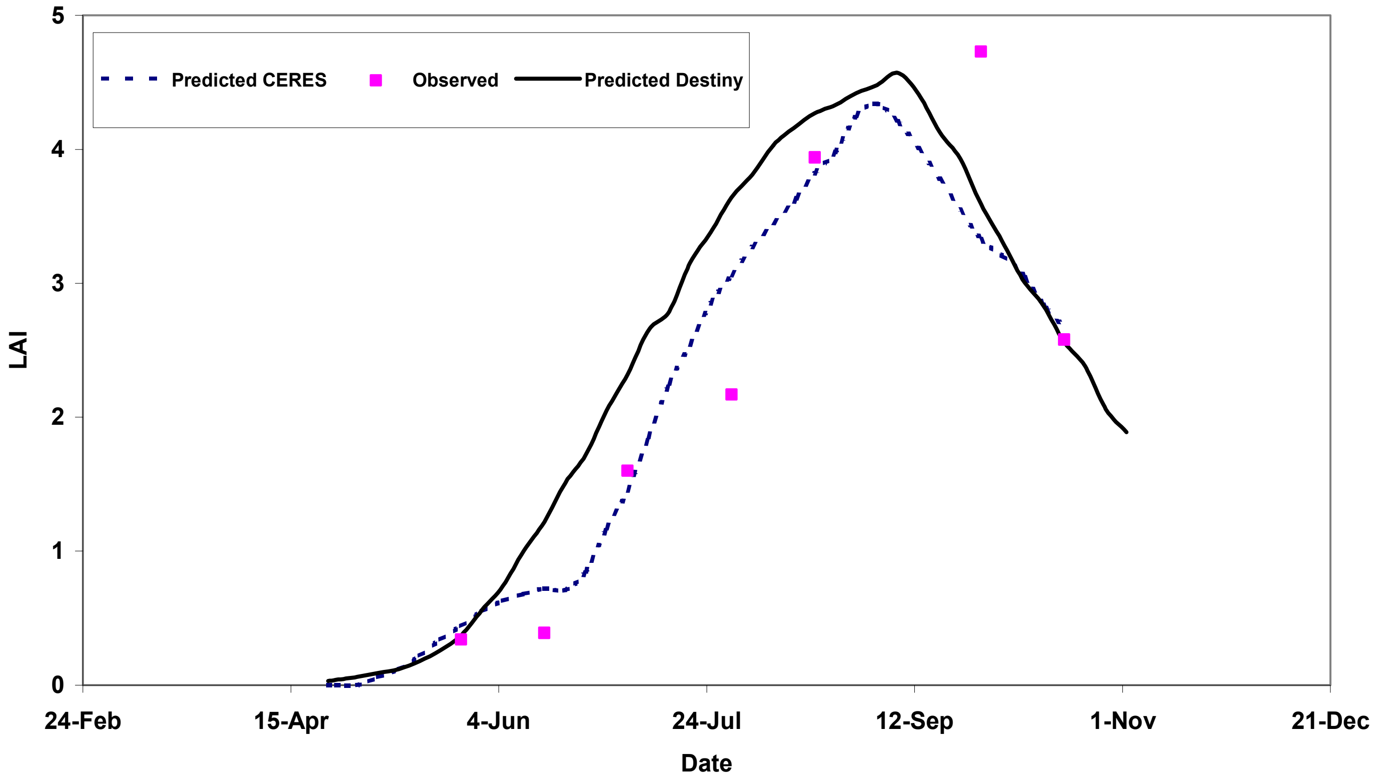

Figure 4. Observed and simulated leaf area index (Early 98).

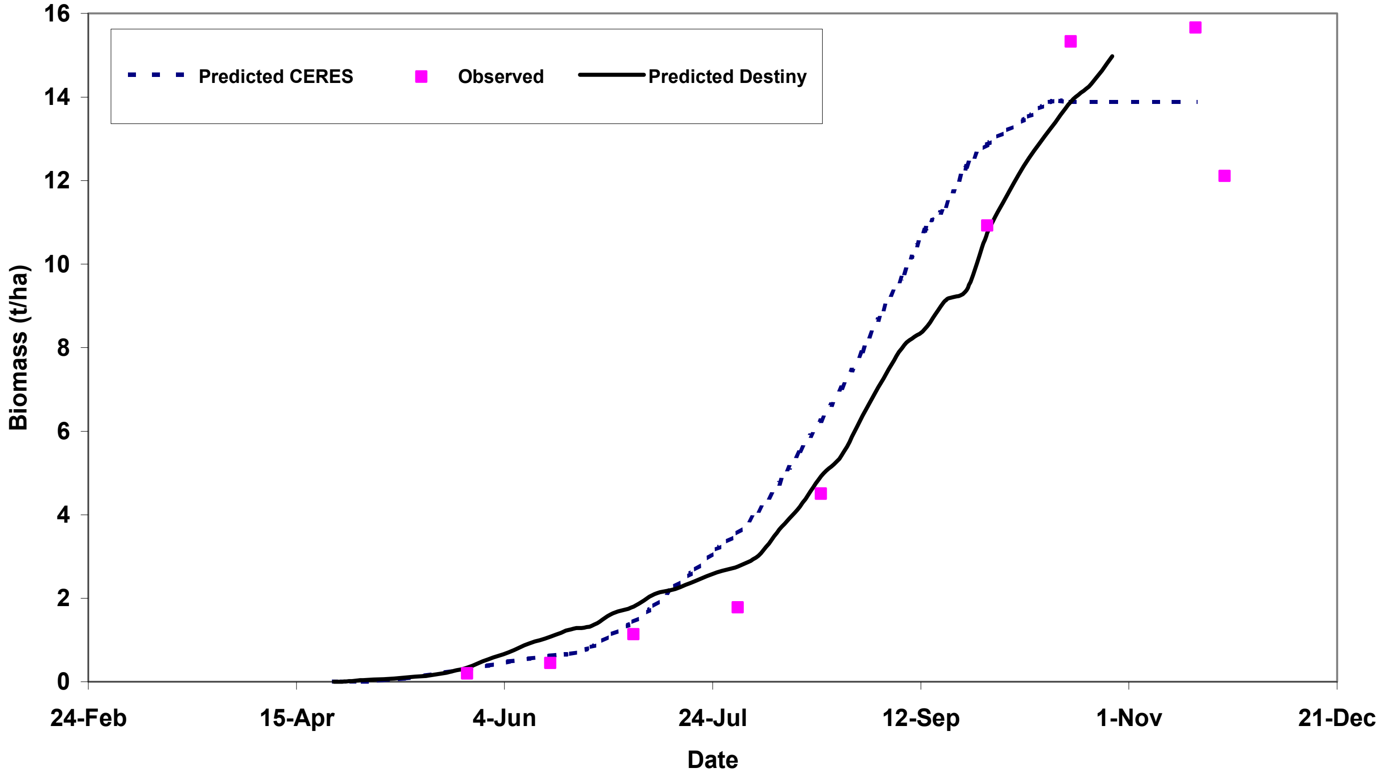

Figure 5. Observed and simulated biomass from (Early 98).

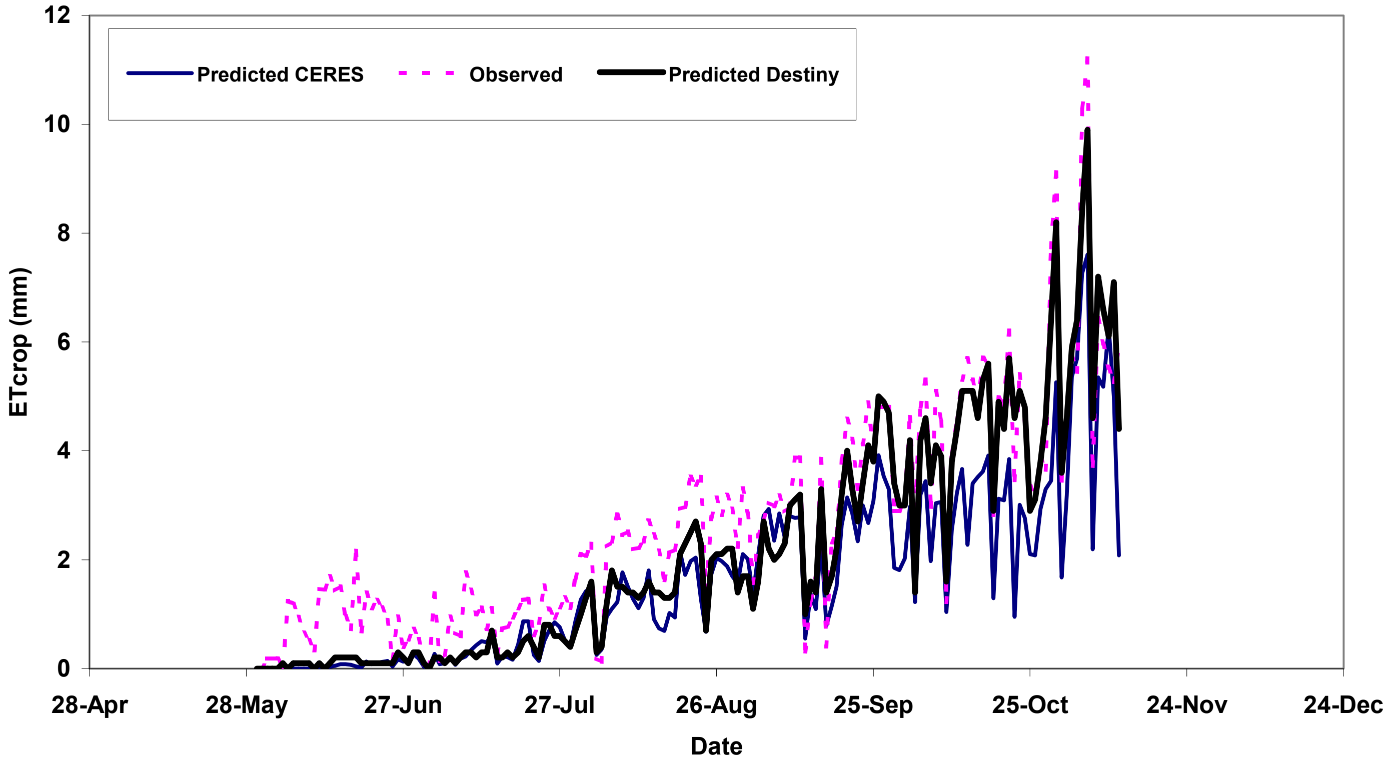

Figure 6. Observed and simulated ETcrop (L186).

Model applications in rice-wheat cropping systems

Timsina *et al.* (2000) used SWAGMAN® Destiny to examine crop productivity options for mungbean grown in the pre-monsoon season in Bangladesh. Mungbean is a short duration crop which can be grown immediately prior to the main wet season rice crop in the rice-wheat cropping areas of Bangladesh. During this season there can be extended periods without rain and also periods of excessive rainfall if the pre-monsoon rains arrive early. SWAGMAN® Destiny was used together with long term weather records to determine tradeoffs between early and late planted crops. Early sown crops are more likely to suffer moisture deficit stress early in the season but can avoid some of the problems of waterlogging late in the season. Later sown crops avoid the earlier water stress but generally are more likely to suffer from waterlogging. The model showed that yields were higher for earlier planting, but that responses to planting time were very much affected by the depth of the underlying watertable (Figure 7). With early plantings, the crop was able to utilize some water from shallow watertables, but the presence of shallow watertables exacerbated later season waterlogging. Yields were much higher where watertables were deep, for all sowing dates. Other simulations suggested the potential for shallow surface drains to increase mungbean yields.

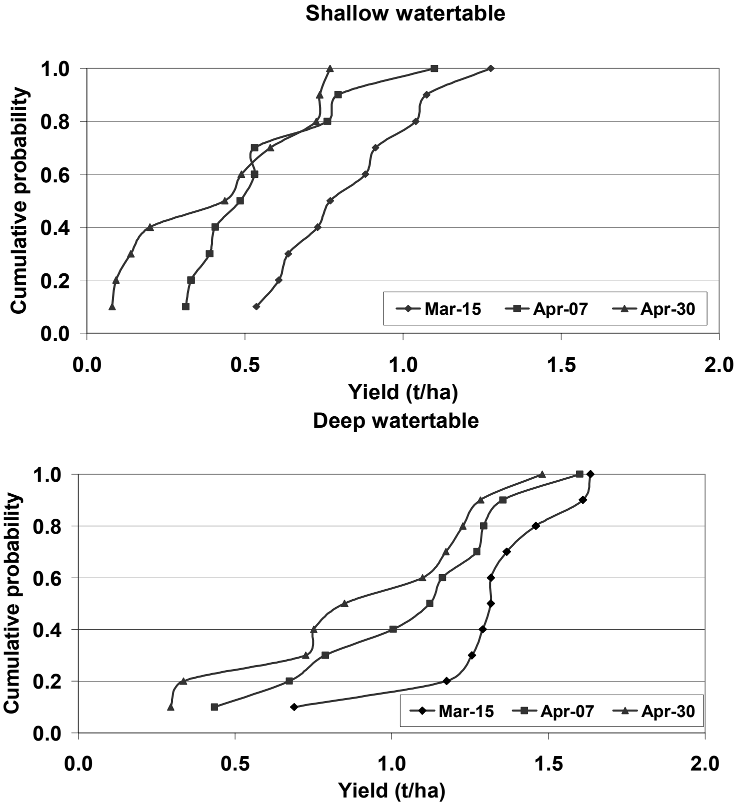

Figure 7. Effect of planting date and water table depth of mungbean on grain yield at Nashipur, simulated using SWAGMAN® Destiny, under non-drained shallow and deep watertable fields with irrigation. The water table depths were set at 0.5 and 5.0 m.

In rice cropping regions of south eastern Australia SWAGMAN® Destiny was used to explore the likely yields of Janz wheat sown after rice on a red clay loam soil, and impacts on watertables and rootzone salinity, for a range of site and management conditions.

Effect of seasonal variability

Yield was determined for 39 different years of weather data (1962-1999) for wheat sown at the end of April ("early") in a situation with a shallow (0.5 m), fresh (1 dS/m) watertable, and no irrigation. Figure 8 shows that yields vary greatly from next to nothing to over 6 t/ha, depending on the incidence and amount of rain. The lowest yield (0.1 t/ha) occurred in 1994 when there were only 58 mm of rain between sowing and maturity, with 20 mm in each of June and July, and virtually no effective rain after that. The results suggest that in about 60% of years, yields of early sown wheat after rice will exceed 3.2 t/ha with no irrigation if there is a shallow, fresh watertable at the time of sowing. The results also suggest that yields would be less than 5 t/ha in 85% of years.

Effect of time of sowing

For exactly the same conditions as in Figure 8, a late sown (end of June) non-irrigated Janz crop has a much lower yield potential. Figure 9 shows that yields are generally reduced by 1-2 t/ha, and will always be less than 4 t/ha, whereas with early sown Janz yield exceeds 4 t/ha in 40% of years (Figure 8). The yield of the late sown crop is lower because it experiences higher temperatures during grain filling, shortening the grain filling period, and because the crop runs out of water towards the end of the season. The yield decline with late sowing is consistent with observations for non-irrigated wheat sown after rice in the field (Humphreys *et al*. 2001).

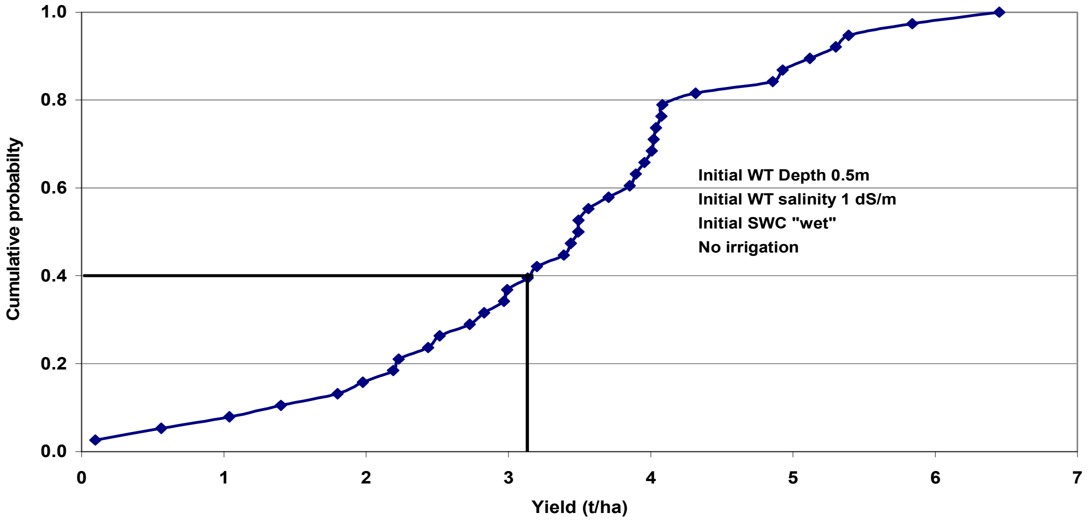

Figure 8. Yield of Janz wheat sown on 24 April, on a red clay loam soil with a shallow, fresh watertable and no irrigation. Initial soil water content (SWC) was "wet" to represent the wet soil profile present after a rice crop.

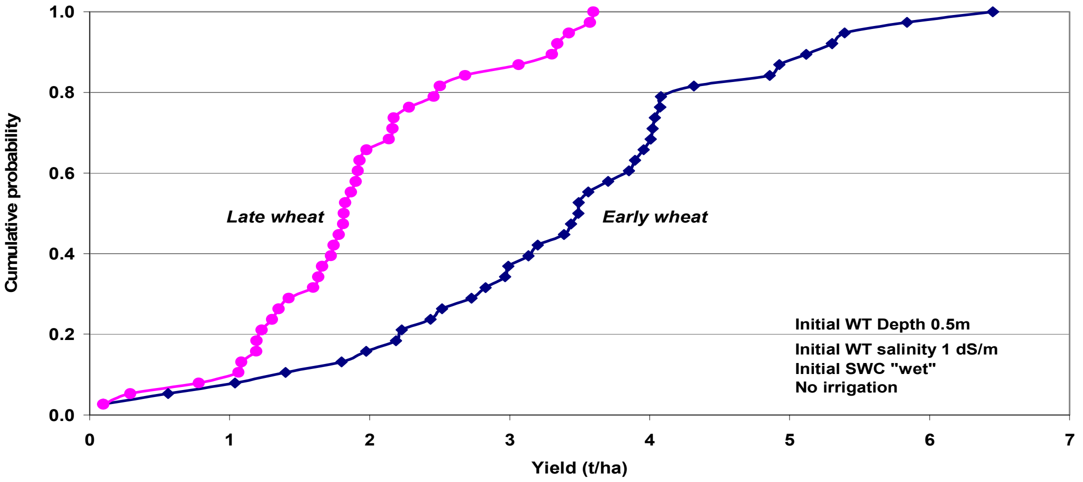

Figure 9. Effect of time of sowing on of Janz on a red clay loam soil with a shallow, fresh watertable, and no irrigation. Early wheat was sown on 24 April, late wheat on 29 June.

Effect of a shallow saline watertable

For early sown Janz after rice, if the watertable is shallow and saline at the time of sowing, and the crop is not irrigated, then yields are much lower than for a fresh watertable (Figure 10). However for an initial 1.5 m deep watertable, yields are unaffected by salinity of the watertable.

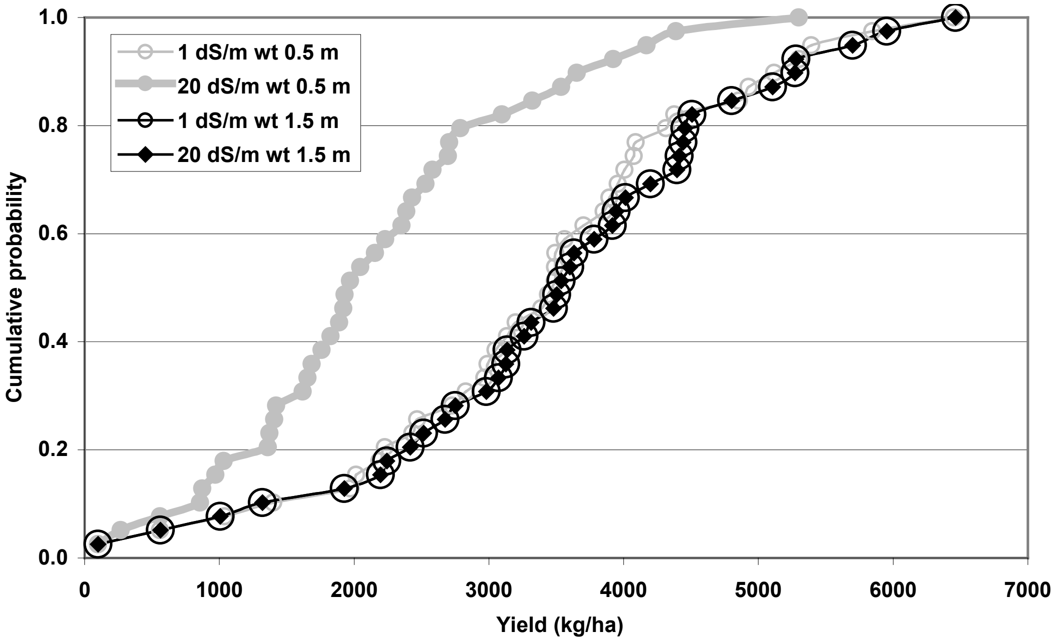

Figure 10. Effect of watertable salinity of yield of early sown Janz sown after rice on a red clay loam, with no irrigation.

Effect of irrigation

A single irrigation during flowering increases yields substantially in most years, and further yield increase is achieved with a second irrigation during grain filling (Figure 11). Frequent irrigation to avoid soil water deficit (e.g. whenever crop water use reaches 60 mm since the previous irrigation) raises yields of both early and late sown wheat for all watertable conditions. The example in Figure 11 is for a shallow, fresh watertable, and shows that yields will exceed 4 t/ha in most years with one irrigation, and 5 t/ha with frequent irrigation.

What happens to the watertable?

Without irrigation, the depth to the watertable is almost always lowered when wheat is sown after rice, except for the wettest of years (Figure 12) in areas where there is a downwards leakage to depth (NB this will not be the case in discharge areas, which occur in parts of the irrigation areas). The lowering is due to two factors – crop water use from capillary upflow from the watertable, and slow downwards percolation of the shallow groundwater to deeper depths. In the example in Figure 12, the downwards leakage rate was 0.1 mm/day and the watertable was at 1.5 m at the time the wheat was sown, and in most years was deeper than 1.5 m at the end of the season with no irrigation.

With 100% efficient irrigation (i.e. assuming that the amount of water added is just enough to refill the soil profile), the watertable at the end of the season is much higher than without irrigation, and often higher than it was at the start of the season (net recharge of the watertable) (Figure 12). In reality flood irrigation is not 100% efficient, much more water is added than needed, and net recharge would be greater than is predicted in Figure 12.

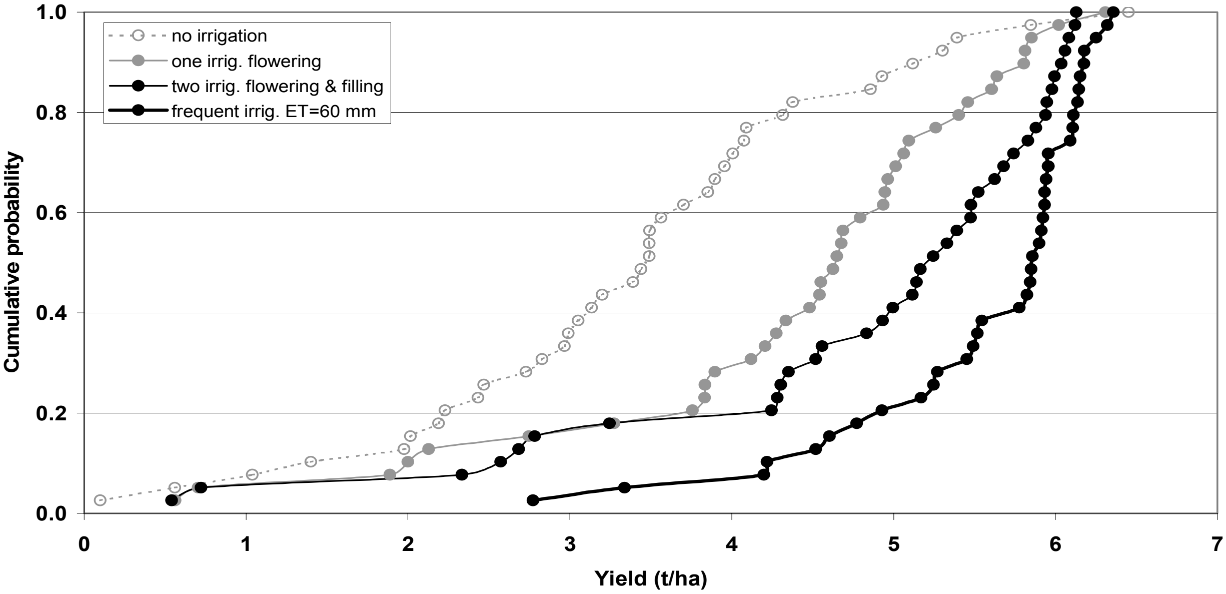

Figure 11. **Effect of frequent irrigation on yield of early sown Janz on a red clay loam soil with a shallow, fresh watertable.**

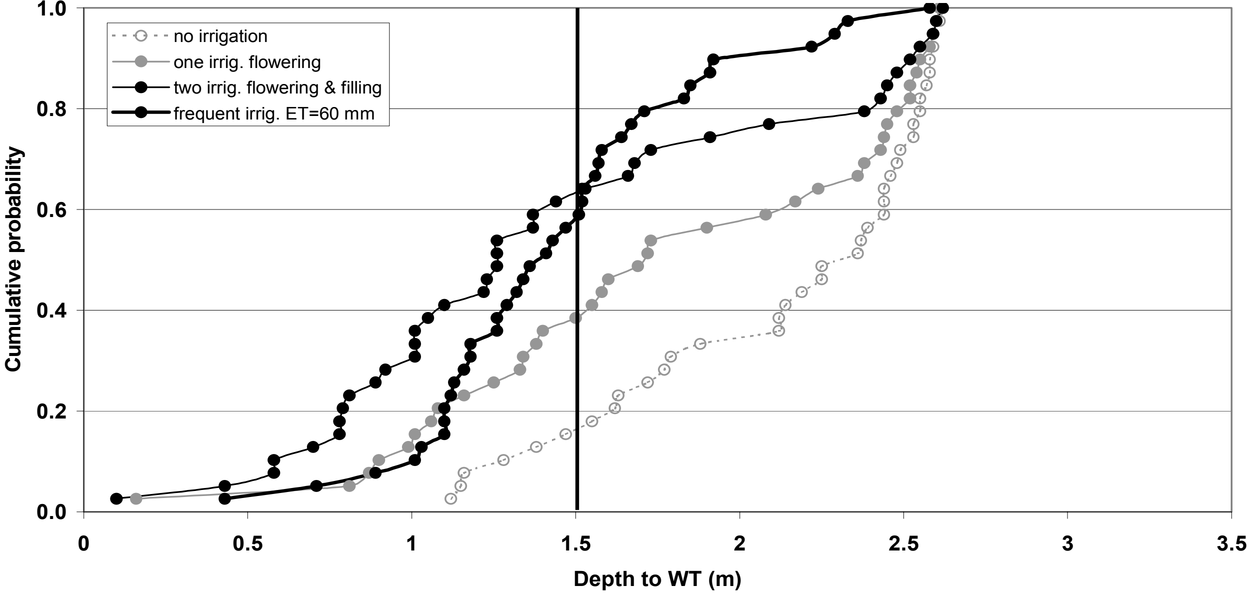

Figure 12**. Effect of 100% efficient irrigation versus no irrigation on the depth to the watertable at the end of the season, for early sown Janz on a red clay loam with depth to the watertable at the time of sowing of 1.5 m.**

Further results are presented in Smith and Humphreys (2001) and Smith *et al*. (2002).

Conclusions

With the capacity to determine both the onset of watertable problems and soil salinisation as well as the impact of these on crop performance, SWAGMAN® Destiny is a useful tool for identifying and examining crop management strategies in rice-based cropping systems which strive to minimise environmental harm and maximize productivity.

References

Agriculture Victoria (1999). Land capability and environmental risk analysis of the Lodden Murray 2000 plus prime development zone. Final report to Lodden Murray 2000 plus Steering Committee. Centre for Land Protection Research, Agriculture Victoria, DNRE, Bendigo, Victoria.

Boland AM, Martin S, Jerie P (1997). Evaluation of critical irrigation quality for perennial horticulture. Project #I5011. Final Report submitted to Murray Darling Basin Commission to develop Natural Resource Management Strategy. 75 pp (plus appendices).

Ghassemi I, Jakeman AJ, Nix HA (1995). Salinisation of Land and Water Resources. UNSW Press Ltd, Sydney (Australia).

Godwin D, Meyer WS, Xevi E, White RJG (2002). SWAGMAN® Destiny: A simulation model of irrigated crops as affected by irrigation practice, watertables and salinity. 1. Model description (in preparation).

Humphreys E, Bhuiyan AM, Fattore A, Fawcett B, Smith DJ (2001). The benefits of winter crops after rice harvest Part 1: Results of field experiments. Farmers' Newsletter Large Area No. 157, pp. 39-42.

Meyer WS (1988). Development of management strategies for minimising salinisation due to irrigation: Quantifying components of the water balance under irrigated crops. AWRAC Research Report, 84/162.

Meyer WS, Dugas WA, Barrs HD, Smith RCG, Fleetwood RJ (1990). Effects of soil type on soybean crop water use in weighing lysimeters 1. Evaporation. *Irrig. Sci*. 11: 69-75.

Meyer WS, Godwin DC, White RJG, Smith DJ (1995). NRMS Cohuna Project. Detailed simulations of upward water movement using SWAGMAN Destiny. A Consultancy Report submitted to Goulbourn Valley Waters.

Smith DJ, Humphreys E (2001). The benefits of winter crops after rice harvest Part 2: Models to predict what will happen in your situation. Farmers' Newsletter Large Area No. 157, pp. 36-38.

Smith DJ, Meyer WS, Barrs HD (1993). Effects of soil type on maize crop daily water use and capillary upflow in weighing lysimeters during 1989/90. CSIRO Division of Water Resources, Technical Memorandum 93/20.

Smith DJ, Meyer WS, Barrs HD, Schwamberger, EC (1996). Lucerne daily water use and capillary upflow using weighing lysimeters: Effects of soil type and groundwater salinity. CSIRO Division of Water Resources, Technical Memorandum 96/6.

Smith DJ, Humphreys E, Godwin, D (2002). Effect of management, site and seasonal conditions on net recharge and yield of wheat sown after rice. CSIRO Land and Water Technical Report (in preparation).

Timsina J, Godwin D, Connor DJ (2000). Watertable management for mungbean within rice-wheat cropping systems of Bangladesh: a simulation study. Proceedings (CD-ROM computer file) of the International Symposium on Systems Approaches for Agricultural Development (SAAD3) symposium. 8-10 November, Lima, Peru.

Xevi E, Smith DJ, Humphreys E, Godwin D, Meyer WS (2002). SWAGMAN® Destiny: A simulation model of irrigated crops as affected by irrigation practice, watertables and salinity. 2. Model testing and evaluation (in preparation).

A version of APSIM with multi-point/spatial capabilities

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Abstract

APSIM version 2, released in 2001, provides capabilities for multi-point simulations. Applications for this functionality include systems where there are spatial issues (e.g. multiple paddocks, agroforestry, windbreak effects) and also systems with smaller scale heterogeneity (e.g. skip rows, beds and furrows). Examples of a windbreak effect and skip row maize are illustrated.

Introduction

The Agricultural Production Systems Simulator, APSIM (McCown et al. 1996) has been developed to provide a flexible framework for simulation of diverse agro-ecological and natural ecosystems. The early releases of APSIM were strictly one dimensional in how they dealt with both above- and belowground components that need to be modelled.

However it has long been recognised that many systems have spatial dimensions that it would be desirable to represent in APSIM models. The types of spatial issues of interest are situations like multiple paddocks (to better represent farming systems, especially those involving grazing animals), agroforestry (to cope with the tree-crop interface), and effects of windbreaks. However it is also recognised that the approach that has been adopted to address these spatial issues might also have application involving heterogeneity at a smaller scale. The multi-point capability became operational in APSM version 2, which was released in the later part of 2001.

In this contribution, we do three things:

- outline the concept that is used to introduce a multi-point capability into APSIM
- show two examples of how this capability has been used – one is a fairly well developed application studying effects of windbreaks (Huth et al. 2002), the other a somewhat preliminary look at how it could be used to study geometry effects in soil at a scale comparable to what might be involve when rice-wheat systems are grown on beds
- finally, we offer some comments on the need for geometry effects in cropping systems models based on experience in modelling other systems where there might appear to be important geometry issues.

Modelling spatial effects using APSIM

Published in Humphreys, E., and Timsina, J. (Eds.) (2002). *Modelling irrigated cropping systems, with special attention to rice-wheat sequences and raised bed planting.* Proceedings of a Workshop, CSIRO Land and Water, Griffith, NSW, Australia, 25-28 February 2002. CSIRO Land and Water Technical Report 25/02.

Normally APSIM is described in terms of the different modules (representing sub-systems such as soil water balance, soil organic matter and nitrogen transformations, growth of different crops) and how these communicate with each other via the "engine". The coupling together of a number of modules to represent a particular situation we will call an "APSIM system".
In the multi-point concept, different APSIM systems communicate with one another, and there are some extra "rules" specifying the nature of the interactions between the separate systems. All the model systems needed to represent the system are simulated concurrently and the interactions are such that the state of the variables in one system can have influence on simulated behaviour in other systems.

Modelling a windbreak

Figure 1 depicts a windbreak. The behaviour to be captured by the model includes the competition zone where tree roots from the trees extend beneath the cropped area and compete for water, and the quiet zone where wind speed is affected by the size of the trees on the edge of the paddock. Figure 2 shows how this agroforestry system can be represented as a number of APSIM systems. There is a single system ("Main") that drives the model and deals with the climate etc, but the plant-soil components are represented by multiple systems: the tree area is split into two units ("inner" and "edge") and the cropping area into a sequence of units moving progressively from the edge of the tree belt into the open paddock.

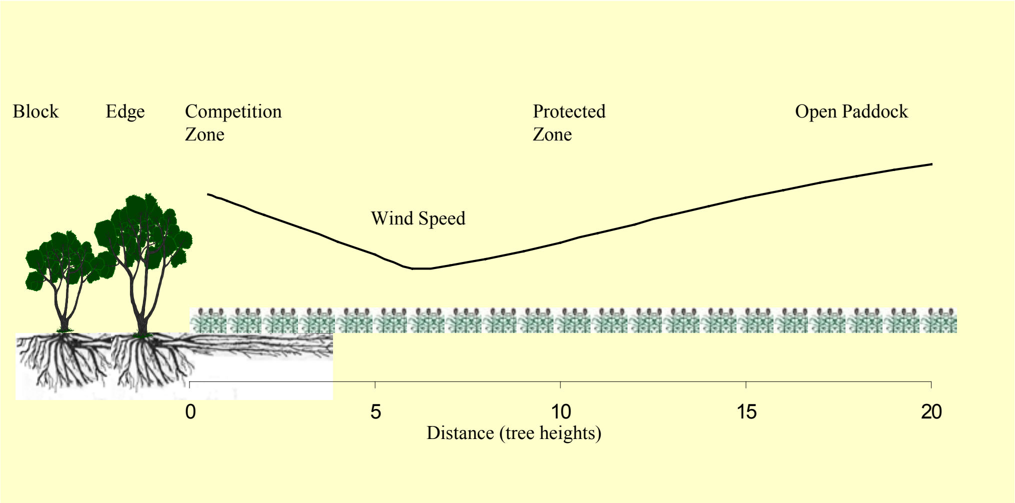


Figure 1. Diagrammatic representation of effects of a windbreak showing root growth from trees extending into cropping area.

The rules for how the different units interact with each other are specified in the module that is included in the "Main" configuration as "Tree Belt". In this case it states how the trees of the "Edge" configuration can extract water from units moving into the cropping area as well as from its own configuration (as would occur with an independent 1D model), and how they impact wind speed down wind from the trees.

Results from such a simulation are shown in Figure 3. Obvious features of the system, such as better growth of the edge trees than the inner trees, less soil water in the cropped area prior to sowing, and reduced growth of the crop near the tree belt, are satisfactorily captured by the model.

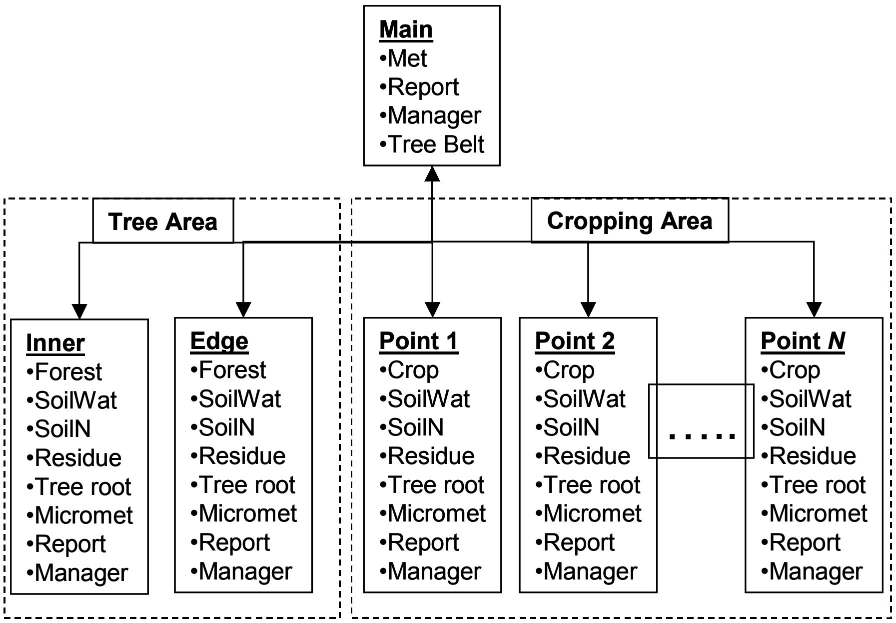


Figure 2. APSIM software configuration of the windbreak example shown in Figure 1

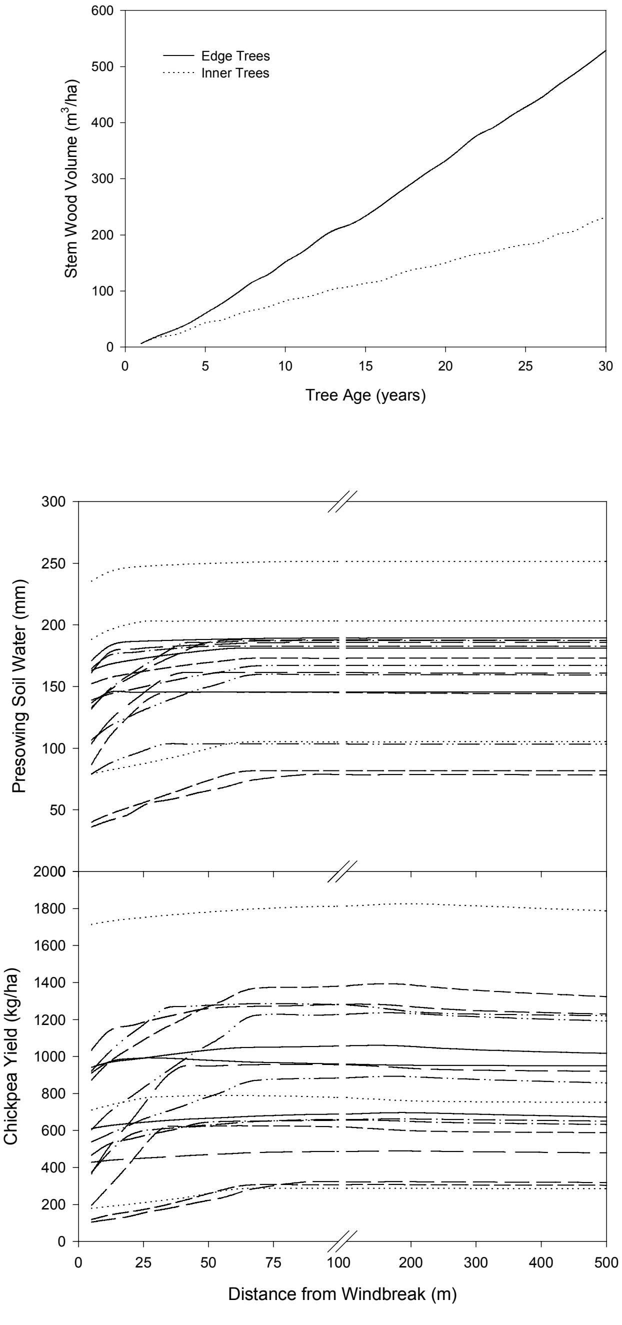


Figure 3. Output from simulation of windbreak effects. Results for pre-sowing soil water and crop yields (lower panes) show output for different years.

Modelling skip row maize

The axes of symmetry in Figure 4 indicate that the system can be reduced to a single 1-D representation of the above ground canopy which resides in the main system configuration and four sub-units to represent the soil (each 0.5m wide). Row-spacing effects on light extinction is handled in the main program.

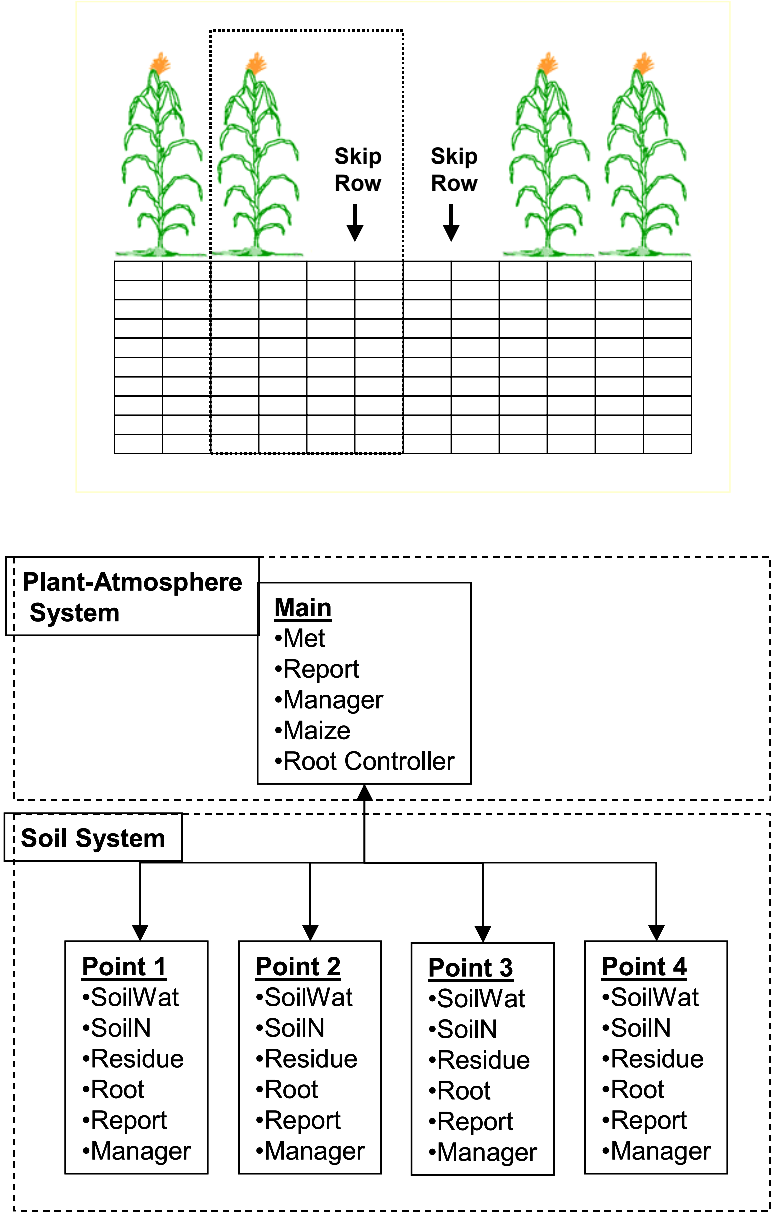
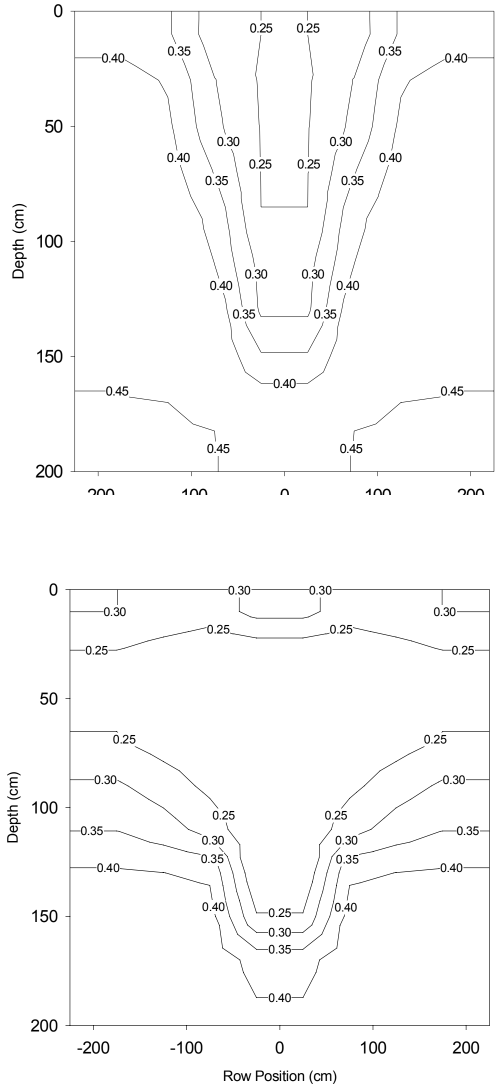


Figure 4. Row spacing of double skip row" maize (rows 1m apart) and APSIM software configuration of the system.

The interactions between the soil sub-units are defined in the "Root Controller". In the example shown at the workshop, the only effects considered were root growth and water uptake. The



maize module in the main configuration will determine the downwards growth of roots in the sub-units directly under the crop. The "Root Controller" then specifies the lateral spread of roots into the adjoining units. The daily output for the four sub-units then permits the construction of the full matrix of distance (across the row / skip row) x depth x time for soil water content.Figure 5 illustrates the pattern of water extraction on two occasions, early and late in the life of the crop. For the simulation shown, the soil was uniformly wet at initialisation. These snapshots in time illustrate how water under the skip rows is used later in the growth of the crop. By maturity, the simulation shows that the upper 60 cm of soil has almost uniform water content across the rows and skip rows, but there is still some difference in moisture content at depth.

Figure 5. Contours of volumetric soil water content under skip row maize early in the growth of the crop (left hand figure) and approaching maturity (right hand pane). The maize rows were located at –50 and +50 cm on the horizontal axis.

In the example that was prepared for the workshop the emphasis was placed on water extraction by the crop roots. However it would seem straightforward to extend the interaction to the uptake of nitrogen, to fertilizer placement effects, and also lateral flow of water between units when water content differs between adjoining cells (a similar algorithm as already used in APSIM SoilWat module (Probert et al. 1998) for unsaturated flow of water within a sub-unit).

On the need for including geometry effects in cropping system models

The growing of rice-wheat systems using beds would seem to call for models that can accommodate the special demands caused by the geometry of the soil surface, the dimension of the beds, and the presence of irrigation water in the furrows. Here we draw attention to somewhat similar features (excluding flooding) that are present in other cropping systems, and where it has been the experience of colleagues that useful simulations have been obtained using strictly 1-D models.

Some systems that have been modeled without addressing seemingly important “geometry issues” include:

- sugarcane which is typically grown on 1.5m spacing with the rows hilled up
    - placement of fertilizer in the hill
    - furrow (& alternate furrow) irrigation systems
    - trickle tape (typically at 30 cm depth), including fertigation
- skip row cotton (also skip row sorghum, maize)
- irrigated cotton
- intercropping (sorghum/pigeonpea; maize/cowpea)

The multi-point functionality now available in APSIM has not yet been applied to any of the systems listed above. However experiments are in progress to study skip row maize (Mike Robertson, unpublished) and these will provide data that will be used to explore the extent to which the multi-point capability improves understanding of the behaviour of this system compared with 1-D models.

References

Huth NI, Carberry PS, Poulton PL, Brennan LE, Keating BA (2002). Simulating Agroforestry Systems Using APSIM. *European Journal of Agronomy* (in press).

McCown RL, Hammer GL, Hargreaves JNG, Holzworth DP, Freebairn DM (1996). APSIM: A novel software system for model development, model testing and simulation in agricultural system research. *Agricultural Systems* **50**, 255-271.

Probert ME, Dimes JP, Keating BA, Dalal RC, Strong WM (1998b). APSIM’s water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agricultural Systems* **56**, 1-28.

Bed experiments at IRRI and China: A Report

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Background

To cope with the increased water scarcity for agriculture, there is a need to develop "water saving irrigation" (WSI) techniques that require less irrigation input than the traditional continuous flooding. WSI techniques include alternate wetting and drying (AWD) irrigations, which allow the soil to dry out to a certain extent before re-applying irrigation water and the cultivation of rice as an irrigated upland crop (aerobic rice). Other technologies are being proposed to save water that entail a more radical change in production technique: the cultivation of rice on raised beds under soil saturation culture. In raised bed systems, water is applied to the furrows infiltrates laterally into the beds. The areal extent of water application is less for flat layouts, and the bed surface is often without standing water, therefore it is hypothesized that the water requirements of rice in raised beds is less than the conventional puddled systems.

Objectives

The objectives of these experiments were to determine the effects of bed configuration (at IRRI), and water regime, variety and fertilizer (in China) on the growth and yield of rice and (2) to determine the water use and water productivity in different bed and water regime treatments.

Methodology

IRRI

In the 2001 wet season (WS) experiments were conducted at 2 sites namely, Block J7-J11 in the lowland farm, and at UX1 in the upland farm, IRRI, Los Baños, Laguna. The experiments have the same split plot design in 3 replications with water regime as the main plot and bed configuration as the subplots. The two sites have contrasting soil properties and water regimes. The lowland site has a relatively low percolation rate since it had been continuously puddled for many more years than the upland site. The soil is also heavier in the lowland site than in the upland site. There was also a large field variability in soil characteristics and soil hydraulic properties in the upland site.

Treatments:

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Water regime (main plots)

- W1 (well watered)
    - B1, B2, B3 (rice on beds): irrigated when water depth is 10 cm below bed surface; irrigated until level with the bed surface
    - B4 (rice on furrow): water depth on the furrow is maintained between 2 to 10 cm above furrow surface
    - B5 (flat bed): continuous flooding, 2 to 10 cm above the soil surface
- W2 (rainfed with supplementary irrigation)
    - Irrigated when soil water potential reaches –30 KPa
- W3 (purely rainfed with survival irrigation)
    - Irrigated when the crop shows signs of stress (leaf score of 3)

Bed configuration : (subplots)

Bed	Bed spacing (center to center in cm)	Bed width (cm)	Location of rice	Tillage
B1	195	155	rice on bed	dry
B2	130	90	rice on bed	dry
B3	65	30	rice on bed	dry
B4	65	30	rice on furrow	dry
B5	flat	flat	conventional	puddled

Crop establishment, variety and fertilizer rates

21 day old rice seedlings (APO) were transplanted at a spacing of 15 cm between rows by 20 cm between hills for all bed treatments. Fertilizer rates were 20 kg N/ha, 30 kg P/ha, 20 kg K/ha, and 5 kg Zn/ha at basal application. At 20 days after seeding (DAS), 20 kg N/ha was applied and 30 kg N/ha at P.I.

Perched water table tubes were used to measure the standing water depth as well as the perched water table. Perched water table depth was measured at different locations across the bed to monitor the subbing. Tensiometers were installed to monitor soil matric potential to indicate time of irrigation. Irrigation amounts were measured using a flow meter. Grain yield and its components were measured.

Tuanlin, China

The experiment was conducted in farmers' fields in a split-split-plot design with three replications. The main plots have four water treatments altogether. They were:

1. Alternate wetting and drying (AWD): Land is prepared as conventional puddled soil. Water is kept at 4-6 cm until 10 DAT (re-greening period). At the end of tillering stage, soil is dried out for 7 to 15 days (mid-season drainage). After this, irrigation follows the AWD (1 to 3 days) cycles.
2. Flushing irrigation (FI). Plots are irrigated quickly with large discharge until the whole surface is covered with water.

3. Rainfed (RF). Field water is maintained during transplanting until 10 date after transplanting (DAT), i.e. re-greening period). No irrigation is given after that.
4. Raised beds (RB). Land is prepared dry and divided into beds and furrows. Rice is transplanted on 0.9 m wide beds. Furrows are about 30 cm wide x 30 cm deep. Water level was raised to about 2–3 cm above the bed surface for transplanting. Water is kept 5–10 cm deep until 10 DAT (green revival period). After that irrigation was provided when water in furrow fell to 20 cm below the bed surface and was irrigated to bring water level to the bed surface.

The subplots consisted of two rice varieties: hybrid rice (2you725) and aerobic rice (HD502).

The sub-subplots consisted of 2-N application rates:
N1: No N fertilizer used but 70 kg P ha^{-1} and 70 kg K ha^{-1} were used. All P and K are applied as basal.
N2: 180 kg N ha^{-1}, 70 kg P ha^{-1} and 70 kg K ha^{-1} were used. 30% of N applied as basal, 30% at 10 DAT, 30% at PI, and 10% at heading. All P and K are applied as basal.

Rice plants were transplanted at a spacing of 20x20 cm and 2 seedlings per hill for hybrid rice while the aerobic rice HD502 was spaced at 27x13 cm at 4 seedlings per hill. The hybrid rice was transplanted on 24 May, and the aerobic variety was transplanted on 15 Jun.

Perched water table tubes were used to measure the standing water depth as well as the perched water table. Irrigation amounts were measured using flow meter. Grain yield and its components were measured.

Preliminary results

IRRI

Irrigation and water depth

There were large variations in soil properties at the upland site which caused a large variation in irrigation water input across replications. Hence, irrigation amounts in the upland field varied tremendously. In the lowland field relatively low irrigation water was applied due to frequent rains. High seepage losses in one W1 plot caused a high variation in irrigation water input. For these reasons, irrigation results are not presented here.

The perched water depth across the beds showed subbing towards the middle of the bed. It was more pronounced in the upland than in the lowland field due to higher vertical permeability of the upland soil.

Grain yield

Grain yields ranged from 2.6 to 4.9 t/ha (Table 1). Yields were higher in the flats compared to the bed treatments. In the lowland field, the widest bed B1 had the lowest grain yield compared to the other bed sizes. In the upland field, there were no significant differences in grain yield among the bed treatments. The higher grain yield in the flats (B5) may be due to the higher plant population (33 hills/m^2) compared to the bed treatments (28 hills/m^2 in B1, 26 hills/m^2 in B2 and 22 hills/m^2 in B3 and B4). Lower yields in the wider beds may be due to less subbing of water from the furrow to the center of the bed as observed in the upland site. Furthermore, yields may also be affected by lower light interception in the middle of the beds compared to plants near the furrows. Plants sampled near the furrows were taller and had more tillers than plants in the middle of the bed.

Table 1. Mean (+ SE) grain yields in different bed configurations at IRRI, Philippines. 2001 wet season

	Mean grain yield (t/ha)	
Bed	Lowland field	Upland field
B1	4.1 ± 0.1	2.8 ± 0.1
B2	4.4 ± 0.2	2.6 ± 0.1
B3	4.3 ± 0.1	2.8 ± 0.1
B4	4.5 ± 0.2	2.7 ± 0.1
B5	4.9 ± 0.2	3.3 ± 0.2

Tuanlin, China

The average grain yield ranged from 4.9 to 9.5 t ha^{-1} in hybrid rice treatments Table 2), and from 0.3 to 1.6 t ha^{-1} in aerobic rice treatments. Low yields in the aerobic riceV2 were due to stem borer damage. Thus, only the results of the hybrid rice will be reported here. There was a significant difference between the nitrogen treatments. In the No-N (N1) treatment, there was no significant difference in yield among the water treatments, However, in +N treatment (N2), AWD had the highest grain yield, while RB had lowest yield. There was no significant difference between the RF and FI. There were also no significant differences between RF or FI compared with the AWD or RB treatment. The RB treatment had lowest grain yield possibly due to lower hill density (21 hills per square meter), while the density of other water treatments was about 25 hills per square meter. Relatively high yields obtained in RF and FI despite low total water input can be attributed to capillary rise from the shallow groundwater table in the site. The groundwater table depth ranged from 0 to 60 cm below the field surface with a seasonal mean of 30 cm.

Table 2. Mean (+ SE) of grain yields in Hybrid rice in different water regimes and fertilizer treatments in Tualin, China. 2001 mid-rice season

	Mean grain yield (t/ha)	
Water Regime	Control	With nitrogen
AWD	5.2 ± 0.4	9.5 ± 0.3
Rainfed	5.0 ± 0.3	8.8 ± 0.2
Flush Irrigation	4.9 ± 0.2	8.8 ± 0.5
Raised Bed	5.4 ± 0.3	8.2 ± 0.1

Irrigation

Irrigation input in hybrid rice ranged from 36 to 490 mm (Figure 1). The highest water use was observed in the AWD treatment in both N1 and N2 treatment. RF and FI had the lower water use compared to AWD or RB. Comparing RB and AWD, RB had lower irrigation input than AWD.

The total water input (rainfall + irrigation) ranged from 324 to 779 mm. Rainfall from transplanting to harvest was 288 mm. RF and FI had the lower water use compared to AWD or RB. Furthermore, RB had lower irrigation input than AWD. Lower water use in RB may be attributed to the smaller area of the furrows compared to the whole plot in AWD (flat). It may also be due to the shallow groundwater table in the site. However, results may be different if the experiment was conducted in a site with deeper water table.

Water productivity

In the hybrid treatment, water productivity (WP) in terms of grain yield per unit of total water input (rainfall + irrigation (I+R)), or (WP (I+R) ranged from 1.34 to 2.44 kg m^{-3}. RF and FI certainly had the higher WP (I+R) among the four water treatments due to less water applied. AWD had the least WP (I+R) among the four treatments. WP (I+R) in AWD was significantly lower than RF and FI. However, it was not significantly different from RB treatment.

Water productivity in terms of irrigation (WP (I)) ranged from 2.3 to 13.2 kg m^{-3}. Similar trends were observed as in WP (I+R).

Issues and concerns in raised bed system

In the raised bed treatments, beds that were formed at the start at land preparation were about 25 to 30 cm high. However, at the end of the season, measurements showed that the heights were reduced to 10 cm. Rainfall and irrigation erode the bed surface and side slopes of the beds especially when the beds are newly formed. Thus, stability of the bed slopes is of great concern if permanent beds are desired.

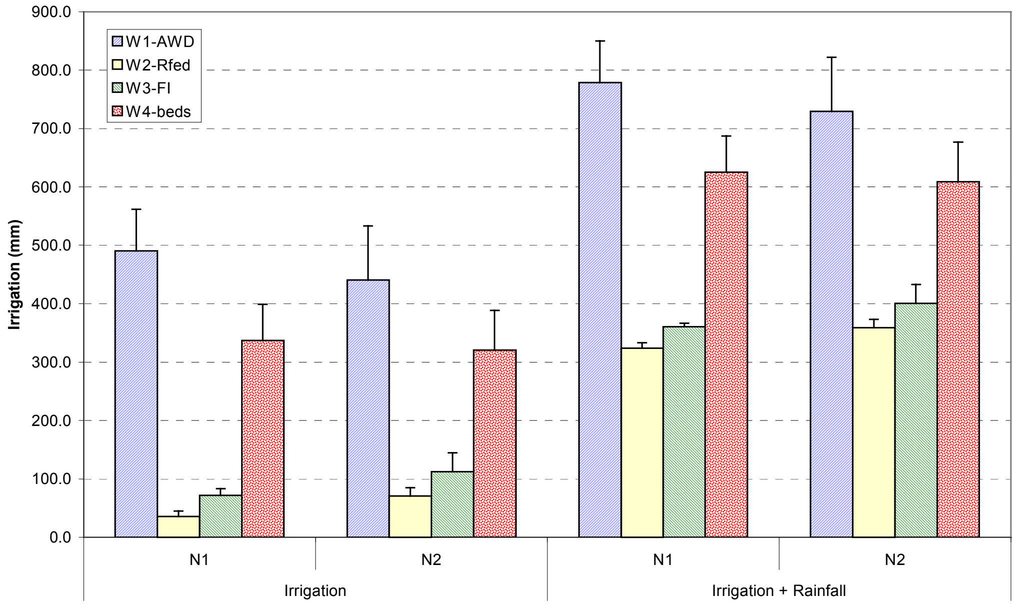
In terms of crop establishment, transplanting on raised beds is a disadvantage. Measurements of time required for transplanting in beds showed higher man-days than in flats. Thus, mechanical transplanting or other crop establishment methods such as direct seeding may be studied in the future.

Uneven bed level is also an important criterion in bed systems. Uneven leveling will lead to non-uniform plants along the bed. Uniform bed level is another constraint in adopting this method. A good land leveling prior to bed forming must be realized.

Weeds also pose a problem in raised bed. Since the bed is often under aerobic conditions, growth of weeds especially of grasses is promoted. Proper weed management techniques in beds must also be developed.

In the 2002 Dry Season, an experiment is ongoing at IRRI, and in China experiments will be implemented in May.

Water input in hybrid rice at Tuanlin



Water Productivity: Tuanlin, ZIS 2001

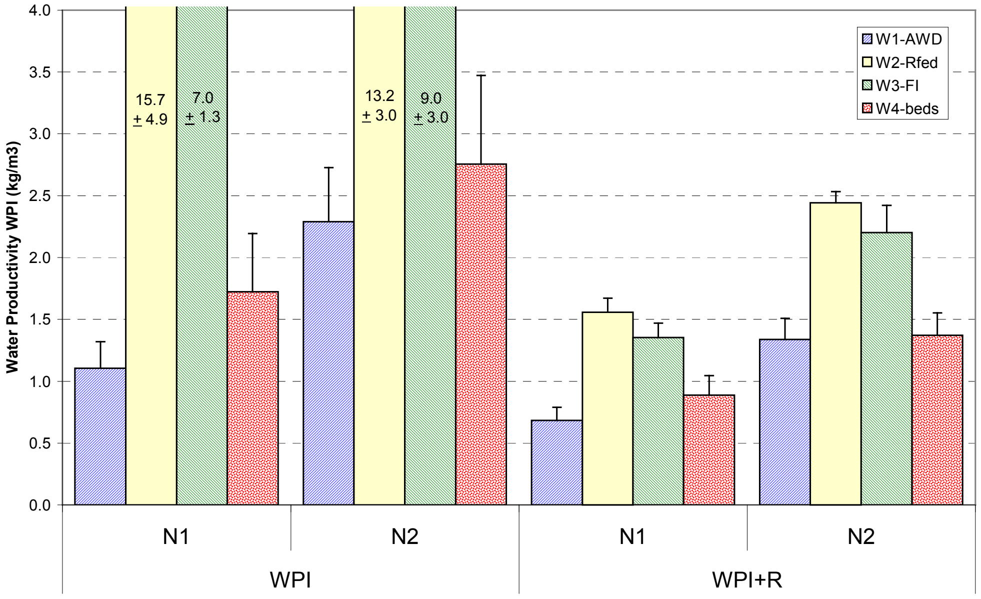


Figure 1. Water input and productivity at Tuanlin

Improved soil management of rainfed vertisol soil in West Nusa Tenggara Province, Indonesia

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In West Nusa Tenggara, Vertisols are the second dominant soil class after Inceptisols occupying broad valley bottoms of fairly level topography. Rice is direct–seeded on nearly 40,000 ha of Vertisols under the gogorancah cropping system. Gogorancah is characterized by rice sown into dry soil and submergence when the wet season starts. This early start allows a secondary crop such as soybeans, mungbeans or maize (following rice) to be grown on residual soil water. Tillage of dry soil (400 mm) is very labour-intensive (200 person day/ha). This system is risky as there may not be enough water for the secondary crop. A collaborative research project funded by the Australian Centre for International Agriculture Research (ACIAR) links LaTrobe University and the University of Mataram in seeking to improve the management of these Vertisols. In this project permanent raised beds are being tested under best crop, soil and water management system. Once set up, permanent raised beds, are less labour-intensive, and have higher water use efficiency (Borrell et al., 1997) than gogorancah. With permanent raised beds, the unused water is being collected during the rainy season, and will be used to irrigate the secondary crop.

Field trials were installed in September, 2001 at two sites on Lombok, Indonesia. There are six major treatments at both the sites: T1 (permanent raised beds for rice and secondary crop under best soil management); T2 (permanent raised beds with soil management and cropping rotation similar to “gogorancah”); T3 (permanent raised beds for vegetable and secondary crops under best soil management); T4 (no tillage, flat with herbicide use for rice and soybean); T5 (intercropping on wavy beds); T6 (gogorancah). Crops were sown at site 1 on 6th and 7th of Dec, 2001 and at site 2 on 19th and 20th of Nov. 2001. Crops were sown after a total of 60 mm of rain over 10 consecutive days. Emergence of sown plants and weeds was recorded. Different soil physical, chemical and biological properties and shifts in water status are being monitored during the trials as is the growth of crops.

Laboratory studies are underway to evaluate the effect of different factors that can improve the physical conditions of heavy clayey soils. Changes in the soil water movement and soil structure are being closely studied in the field experiments. Possible factors responsible for these changes are being studied in the laboratory to understand the processes causing these changes. Results of these laboratory studies will help in understanding the long-term affect of these factors in the fields.

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Key questions for modelling

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An important question for workshop participants was "what do we want to achieve through the application of models in the ACIAR project? – what are the key questions that we want the models to help us to answer?".

A suggested key question was:

Does rice-wheat on permanent beds "perform" better than on conventional layouts/management (puddled translanted rice followed by conventionally tilled wheat on the flat), and under what conditions?

"Performance" criteria

- component crop and total crop yields
- component crop and total system water use
- non-beneficial evaporative loss (from soil surface and floodwater)
- deep drainage beyond the rootzone
- partial factor productivity (N, water, other?)
- greenhouse gas emission (beyond the scope of this project)
- pollution of groundwater (related to deep drainage)

How is this affected by…..

Management

- sowing/planting date
- method of rice establishment (e.g. dry-seeded rice, transplanted rice)
- bed geometry (width, height, furrow width)
- row/plant spacing
- irrigation management (time, amount)
- N management (placement, time, amount, source)
- mulching/stubble management
- soybeans instead of rice

Site

- soil type

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- watertable depth and salinity
- irrigation water salinity
- weather variability (within a climatic region)
- climate (beyond the scope of this project)
- climate change

Factors influencing the performance of rice-wheat on beds, for which current crop models would not be of assistance, include:

- weeds
- diseases, pests
- nutrients other than N
- other inputs e.g. diesel, labour
- changes in soil structure over time
- bed stability

Issues and opportunities for modelling rice-wheat crop sequences on flat and bed layouts

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Gaps between potential yields and farmers' and researchers' yields

An important role for crop models is the estimation of yield potential and yield gaps at regional and site specific scales, identification of reasons for the gaps, and evaluation of management options for closing the yield gaps.

Average rice-wheat (RW) system yields in farmers' fields in India (5.5 t/ha) and in the state of Punjab (7-8 t/ha) are much lower than potential yields (Timsina and Connor 2001; Narang and Virmani 2001). Based on a grain-filling duration of 25 days and total growth duration of 100 days for each stage, average daily solar irradiance of 15 MJ/m^2/day, and radiation-use efficiency of 1.5 g dry matter/MJ short-wave radiation, Timsina and Connor (2001) estimated yield potential of 14 t/ha for the RW system in the IGP (7 t/ha each for rice and wheat). Aggarwal et al. (2000a) estimated potential yields of rice and wheat for several states of India using ORYZA1N (Bouman et al. 2001) and WTGROWS (Aggarwal et al. 1994). They (Aggarwal et al. 2000b) determined potential yield of 16.0 t/ha (rice 9.0 t/ha and wheat 7.0 t/ha) for Delhi using CERES-rice and CERES-wheat model. Using the CERES models under the sequence mode of DSSAT (Thornton et al. 1994), Timsina et al. (1996) estimated potential yields of about 13 t/ha (rice 7.5 t/ha and wheat 5.5 t/ha) for RW systems for Pantnagar, Uttar Pradesh. Thus there appear to be large gaps between yield potential and actual yields being achieved by farmers in RW systems.

Long-term yield trends, and yield decline or stagnation

Yield stagnation in RW systems is a major concern for food security in south Asia. Yield decline does not appear to be as extensive or serious as previously suggested: long term experiments show that rice yields have declined in a small number of locations, and there is good evidence of yield decline in wheat in a very few locations (Dawe et al. 2000; Yadav et al. 2000). While there are several "standalone " models for each of wheat and rice, few models exist which can simulate sequences of wheat and rice and the intervening fallow period. There are issues in the RW system of carryover of soil organic matter as well as nutrients and water between phases. Models suitable for examining long term yield trends require the capacity to address these issues. Timsina et al. (1996, 1998) used the DSSAT RW sequence model to satisfactorily simulate yields of a longterm RW experiment at Pantnagar, India, and to study long-term yield trends at

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Nashipur, Bangladesh. These are the only examples of application of a crop sequence model to RW systems that we are aware of, and further validation and testing of the DSSAT RW model is required.

Global climate change

Global climate change will impact on yield potential and production through changed weather and atmospheric carbon dioxide concentration, affecting crop growth and development, irrigation demand, and the supply of irrigation water. Analysis of the effects of climate change on yield potential, and its consequences for yield gaps and water resource requirements, requires the application of rigorously tested and validated crop models, calibrated for key species and current varieties. There is potential for the ACIAR project to contribute towards this effort. The DSSAT/CERES models have been used in a variety of climate change studies and thus have appropriate linkages built into the growth and water balance routines to readily examine climate change scenarios (Singh et al. 2002). RW cropping systems can also be significant contributors to greenhouse gas evolution via the evolution of carbon dioxide from organic matter decomposition, via nitrous oxide evolution from aerobic soils, and via methane evolution from anaerobic (saturated or flooded) soils. Models that can describe the transformations of N in flooded soils (CERES Rice) and methane evolution (MERES – derived form CERES) (Matthews et al. 2000) can contribute significantly to quantifying greenhouse gas evolution and the impacts of water, stubble and nitrogen management.

Tillage

Most areas under RW systems in the IGP are heavily tilled for both crops, including puddling for rice, however zero or reduced tillage for wheat after rice is expanding rapidly. In southern NSW the soil is less heavily tilled for rice than in the IGP, but is typically tilled to 5-10 cm depth with one pass of offset discs and one pass with tynes or harrows, followed by one pass with a ridge roller for water seeded rice. Where wheat is grown immediately after rice harvest, it is typically direct drilled using a triple or double disc, or sometimes with an air seeder with narrow points.

Puddling affects soil structure in many ways, with benefits for the rice crop including softer soil for rice root growth and reduction in percolation rate. However there is much evidence that soil structure is impaired for crops grown after rice (e.g. formation of a plough pan, massive soil structure and cracking), but the effect on performance of crops after rice is variable, and may depend on soil type and management (Connor et al. 2002).

CERES rice simulates the effect of changes in percolation rate and bulk density associated with puddling and the reversion to a non-puddled state. The components of the model to describe puddling effects are rudimentary and would require further work to determine how well they work in the coarsely textured soils of NW India. A new tillage routine has been introduced into the DSSAT framework which can redistribute organic matter and make changes to surface infiltration properties. This needs to be evaluated for RW systems.

Simulating the effect of tillage with a particular machine on a given soil in a given condition, and how soil condition changes over time, would be extremely challenging. The implications for our ability to model soil water/aeration/N dynamics in switching from conventional cultivation to direct drilling (with or without beds) remain to be seen.

Soil organic matter (SOM) management and residue management

There is a concern about the decline in soil organic carbon (SOC) in RW systems in the IGP, however its implications for yield and connections with yield decline are not apparent. Most rice and some wheat residues in Punjab and Haryana are burnt. Most rice and wheat residues in southern NSW rice-based cropping systems are burnt.

The original version of DSSAT 3.0, with one soil organic matter (SOM) pool, did not accurately simulate the long-term decline in SOC and total N in a long-term experiment at Pantnagar, India (Timsina et al. 1996). In the modified SOM routine (Gijsman and Bowen 2002) of DSSAT 3.5, based on the CENTURY model, there are three SOM pools (passive SOM, slow SOM, and active microbial SOM), one SOM pool on soil surface (microbial SOM), and two litter pools (in the soil and on soil surface). In contrast to the earlier version, the SOM and residue flows now vary with soil texture. The APSIM soil OM model has been evaluated under various sequences in wheat based cropping systems but lacks components for flooded soil turnover of C and N. The new version of the DSSAT, which also incorporates detailed flooded soil C and N dynamics, requires rigorous testing. Thorough evaluation of the models under DSSAT to simulate changes in SOC in response to different stubble management treatments is beyond the scope of the ACIAR project. This would require a long-term project, and much better understanding of the pools of SOM that would need to be measured than is currently available. Furthermore, change in SOM content and composition has implications for soil structure and soil water and aeration dynamics.

Soil chemistry (N, P)

Changing from puddled ponded rice culture to non-puddled intermittently irrigated bed systems will have major implications for soil N transformations and transport. A major strength of the CERES rice model is its ability to handle fluctuating water regimes and their impact on N transformations and transport. CERES rice simulates nitrate and urea transport in the soil, ammonia volatilization from floodwater, and movement of nitrate, urea and ammonium between the floodwater and the soil. It does not, however, simulate ammonium leaching which Katyal et al. (1985) found to be significant in the coarse-textured soils of Punjab. Description of this process needs to be incorporated in the CERES models. Since CERES Rice has the capacity to simulate ammonium exchange between the surface soil layer and floodwater it should be possible to simulate ammonium fluxes in the soil. The ability of CERES rice to simulate the N dynamics for a non-uniform bed geometry needs to be tested for the "average" situation, and for points in the system (e.g. middle of bed, edge of bed). CERES Rice has well developed routines that simulate response to uptake of N, tissue %N and growth processes. ORYZA 2000 (Bouman et al. 2001), a successor to a series of rice growth model developed under SARP (Simulation and Systems Analysis for Rice Production) Project in 1990s at IRRI, also simulates tissue %N, N uptake and growth processes, but not rigorously the soil or floodwater transformations of N.

The CERES wheat model currently does not simulate ammonia volatilisation, and this can be an important loss process on the calcareous light textured soils of the Punjab where urea and ammonium fertilisers are broadcast onto the soil surface. The potential for ammonia volatilisation is likely to be high on furrow-irrigated beds if N fertiliser is broadcast on the bed surface. An adaptation of the floodwater ammonia volatilization routines from CERES Rice to soil surface ammonia volatilization for Punjabi wheat growing conditions should be possible.

The anaerobic/aerobic transitions in traditional RW systems also have major implications for P availability, and the impact of changing from traditional systems to intermittently irrigated bed systems needs to be understood. There has been some work on incorporating P into the upland DSSAT models, and capabilities of DSSAT with regard to P for RW sequences need to be explored.

Matching crop species and cultivars to local conditions

Simulation modelling offers the ability to help match species and cultivars to local conditions, for the range of likely climatic variability, simply by varying sowing dates. However the genetic coefficients of the varieties of interest need to be determined by rigorous calibration. Varietal duration and effects of temperature and radiation are major considerations.

To better fit the 2 crops, and in some instances 3 crops, into the RW system of the IGP, there is a need to develop better early- or medium-maturing cultivars of both rice and wheat crops. While doing so, the effect of crop duration on yield potential needs to be considered as there is generally positive relationship between yield and crop duration.

In RW systems, wheat is often sown late (for a range of reasons), and hence suffers from high temperatures during the flowering and grain-filling stages. High temperature shortens the grain-filling period and may also induce water stress leading to slow growth rates and sterility. As a consequence, grain yield of wheat decreases substantially as sowing is delayed beyond the optimum date. Early or medium maturity of both rice and wheat crops would be a desirable character, with additional traits for wheat to cope under high temperature conditions.

Though DSSAT models have very strong and detailed phenology routines, recent experience has shown that in trying to broaden the range of environments where the CERES-wheat model is being tested, its temperature response (e.g. temperature vs. phenology, grain yields and partitioning to grain, etc.) against data from international trials of CIMMYT has been unsatisfactory (White et al. 2000), and so the model is currently under review (personal communication with Tony Hunt, University of Guelph and Jeff White, CIMMYT, Mexico). Likewise, the phenology routine of CERES rice (e.g. for growth and development as affected by stress factors such as water deficit, N deficit) is also under revision (personal communication with Upendra Singh, IFDC). Nevertheless, the current versions of DSSAT models provide a fairly good framework for simulating crop cultivars for intensive cropping systems, but will be better with further improvements

Soil water

Many currently available models (DSSAT, SWAGMAN Destiny, APSIM, the Wageningen models, etc.) can satisfactorily simulate soil water dynamics and components of the water balance during the growing season, despite using differing approaches (e.g. mechanistic approaches based on Richard's equation, or functional approaches as used in the CERES models). The choice of water balance simulation approach is most often decided by availability of input data. All models still have problems with cracking soils. SWAGMAN Destiny and DSSAT can also simulate the interaction with a shallow watertable. In addition, SWAGMAN Destiny simulates the effect of waterlogging (aeration stress) on upland crops, and salt dynamics and salt stress (Godwin et al. 2002). An example of application of SWAGMAN Destiny for managing waterlogging through providing shallow surface or sub-surface drainage for pre-kharif season mungbean in RW systems of Bangladesh has been provided by Timsina et al. (2000). It needs further testing.

Issues for sequences

Two approaches for simulating crop sequences are:

(i) string crop models together, and add a fallow model for in between periods e.g. DSSAT
(ii) construct a soil focused model coupled with crop models and soil perturbation models e.g. EPIC, APSIM, SALUS

The models need to be able to carryover state variables from the end of one crop (or fallow) to the start of the next crop. The main state variables that need to be carried over are soil water content in the different soil layers, soil temperature, soil nutrients (N), SOM (amount, pools, nature - C:N), watertable depth and salinity and soil salinity. An important issue is what happens in the fallow period, for example, there will be implications for N, soil water and the distribution of organic matter across layers depending on whether a fallow is bare, tilled, weedy or grazed, and simulation of the water, N and SOM dynamics over the fallow period is essential. Systems models needs the capacity to simulate whatever is happening between crops.

DSSAT and APSIM both provide a framework for simulation of cropping sequences, so that soil water, residual N, and organic matter status at harvest of one crop become the starting conditions for the next. APSIM does not yet have a rice model and thus cannot simulate RW sequences. There has, however, been limited testing of CERES rice and wheat models for sequences in the IGP, and further testing is needed using the latest version of DSSAT with the new SOM routine. Further, the sequence routine in the current version of DSSAT is not user friendly, mainly due to irrigation switches for rice and rules for sequencing. The rules for automatically running crop sequence models need to be very site specific, and must include decision rules (e.g. rules for irrigation, N application, drainage) and rules that account for factors such as the effect on the choice of variety if sowing is delayed due to delay in harvest of the previous crop. The sequence routine is under revision (personal communication with Jim Jones, University of Florida and Upendra Singh, IFDC).

ROTAT_RW (Bouman et al. 1994) is a rice-wheat sequence modal that can simulate carry-over effects of soil water but not N-related processes. ROTAT_RW is based on ORYZA_W for rice (Wopereis et al. 1996), WHEAT_W for wheat (van Laar et al. 1992), and WATBAL for water balance (Wopereis et al. 1993). WHEAT_W is based largely on SUCROS (Spitters et al. 1989). WATBAL can simulate the water balance of both puddled and non-puddled soil. There has also been limited testing of ROTAT_RW for RW sequences (Timsina et al. 1994).

Cropping systems on beds

Changing from traditional flat to a permanent bed system will have major implications in terms of tillage and residue management, water and nutrient dynamics, and light interception. On the flat with flood irrigation, movement of water, nutrients and salts is generally in the vertical plane, or one-dimensional. However, on beds with furrow irrigation, there will be both vertical and horizontal components of movement (2-dimensional) from the furrows into the beds. Furrow irrigation will result in variable soil water status across and below the bed-furrow system. This will affect fluxes of water and solutes, and transformations of nutrients. It is generally expected that losses through evaporation and deep drainage could be reduced with intermittently irrigated bed layouts, but deep drainage losses could also be higher from the furrows than from conventional puddled flooded systems.

Switching to bed layouts may have little impact on water availability for crops (provided bed geometry and water management are managed to meet crop water requirements), however it may have major implications for N availability to the crop due to effects of the changed hydrology on N transformations and transport. If N is not managed carefully, intermittently irrigated bed layouts for rice will predispose the system to high N losses. For example, topdressing onto the moist bed surface could lead to high losses by ammonia volatilization, especially on alkaline soils. The frequent wetting and drying cycles with intermittent irrigation of rice also suggest the potential for high losses from nitrification/denitrification, therefore the fertiliser needs to be placed where the soil remains wet. There is also the potential for transport of nitrate to the bed surface by capillary upflow, where it would be unavailable if the soil surface remained dry for extended periods, as is the case in winter which is generally dry (i.e. throughout the wheat season).

However, switching to bed layouts with mechanization also offers new opportunities for improved management of N fertilisers. For example, banding N fertiliser below the surface of the beds, under the rows or centre of the bed prior to sowing, and between the rows for later applications, would reduce ammonia volatilization losses. The distribution of wheat roots at the early jointing stage (see Photo 1) suggests that banding of fertiliser below the bed surface at sowing, followed by application into the furrows before irrigation or applying it in the irrigation water at the end of the tillering stage, would be a very efficient method of N application for wheat. In this photo, there is a mass of older wheat roots below the centre of the bed, and prolific growth of younger roots under the furrows. The topsoil in the IGP is a loamy sand, with a sandy loam subsoil. The development of the bed former/seeder and the portable machine for making supergranules also provides the opportunity for deep placement of urea or combination fertiliser supergranules (Photo 2).

Recommendations for the ACIAR team

1. DSSAT version 3.5 is the best starting point for modelling RW systems since it has well developed and tested rice and wheat models, and the capability of carry-over of key state variables such as water, N and C. The latest version of DSSAT (with new tillage routine and SOM module) needs to be validated/tested against field data sets from crop sequence experiments from Yanco and Deniliquin in NSW, and from Punjab in India. This will help to identify any weaknesses in the models, what to measure, and what to model. The latest version of DSSAT has a modular approach as described by Jones et al. (2001, 2002). This version should be obtained as soon as possible from the ICASA, or from the University of Florida (Jim Jones), or IFDC (Upendra Singh). The cold damage routine developed by Godwin et al. (1994) needs to be incorporated into the rice model in the latest version of DSSAT.

2. Crop sequencing capability needs to be incorporated into SWAGMAN Destiny to enable investigation of groundwater, waterlogging and salinity issues.

3. Initial investigations using the models should be made to estimate the potential yields of component crops for sequences in both Punjab and NSW. The models need to be applied to identify risks associated with sowing/planting date of component crops, method of rice establishment (DSR, TPR), row/plant spacing, irrigation management (time, amount, etc.), N management (placement, time, amount, source, etc.), mulching/stubble management, and growing soybean instead of rice for a range of sites (soil, watertable, climate), management and seasonal conditions.

4. In the short-term, the ability of 1-dimensional models to simulate the "average" system needs to be assessed, followed by consideration of the potential gains from a 2-point approach, using DSSAT and SWAGMAN Destiny.

5. At the same time, some initial investigations using a 2-dimensional model (e.g. HYDRUS 2D; Simunek et al. 1999) (and/or other such model (e.g. FUSSIM2; de Willigen 2002) should be used to investigate water and solute dynamics for a range of bed geometries and soil types.

6. Some of the key processes that need to be modelled initially for bed systems are vertical and horizontal fluxes of water and N, N transformations across beds and furrows, and radiation interception across beds and furrows. Measurements of soil water status and mineral nitrogen, across the beds/furrows and with depth, and of light interception across the beds/furrows, are crucial to help understand the effect of the bed geometry on crop response to water and nitrogen management.

Photo 1
Root distribution of wheat growing on beds in Ludhiana, Punjab, India – 2 rows per bed

Photo 2. Bangladeshi supergranule making machine modified by the Rice Wheat Consortium for greater portability (wheels, powered by PTO) and to make round granules.

References

Aggarwal PK, Talukdar KK, Mall, RK (2000a). Potential Yields of Rice-wheat System in the Indo-Gangetic Plains of India. Rice-wheat Consortium paper Series 10. RWC for the Indo-Gangetic Plains. IARI Campus, Pusa, New delhi 110012, India. 12 pp.

Aggarwal PK, Bandyopadhyay SK, Pathak H, Kalra N, Chander S, Kumar S (2000b). Analysis of yield trends of the rice-wheat system in north-western India. *Outlook on Agric*. **29**, 259-268.

Aggarwal PK, Kalra N, Singh AK and Sinha SK (1994). Analysing the limitations set by climatic factors, management and genotype on productivity of wheat. I. The model documentation, parameterisation and evaluation. *Field Crops Res*. **38**, 73-91.

Bouman BAM, Kropff MJ, Tuong TP, Wopereis MCS, ten Berge HFM, van Laar HH (2001). ORYZA2000: Modeling Lowland Rice. IRRI, Los Banos (Philippines). 235 pp.

Bouman BAM, Penning de Vries FWT, Wan Harun WS, Timsina J, Hartkamp AD (1994). Optimising rice-wheat rotations under water-limited conditions. Paper presented at the symposium “Scenario studies for the rural environment”, 12-15 Sept 1994, Wageningen, Netherlands, and the “Third Congress of the European Society for Agronomy. 18-22 Sept 1994, Podowa, Italy. 4 p.

Connor DJ, Timsina J, Humphreys E (2002). Prospects for permanent beds for rice-wheat systems. ASA Special Book. ASA-SSSA-CSSA. USA (in press).

Dawe D, Dobermann A, Moya P, Abdulrachman S, Bijay Singh, Lal P, Li SY, Lin B, Panaullah G, Sarim O, Singh Y, Swarup A, Tan PS, Zhen Q (2000). How widespread are yield declines in long-term rice experiments in Asia? *Field Crops Res*. **66**, 175-193.

de Willigen P, Heinen M (2002). A short description of the simulation model FUSSIM2 illustrated with two examples. Pp. 57-62, In: Humphreys, E, Timsina, J (Eds.), Modelling irrigated cropping systems, with special attention to rice-wheat sequences and raised bed planting. Proceedings of a workshop at CSIRO Land and Water, Griffith (Australia) 25-28 February 2002.

Gijsman AJ, Hoogenboom G, Parton WJ, Kerridge PC (2002). Modifying DSSAT for low-input agricultural systems, usinf a soil organic matter- residues from CENTURY. *Agron. J.* **94**: 462-474.

Godwin DC, Meyer WS, Singh U (1994). Simulation of effect of chilling injury and nitrogen supply on floret fertility and yield in rice. *Aust. J. Exp. Agric*. **34**: 921-926.

Godwin DC, Meyer WS, Xevi E, White RJG (2002). SWAGMAN Destiny: a simulation model of irrigated crops as affected by irrigation practice, watertables and salinity. I. Model description (In preparation).

Jones JW, Keating BA, Porter CH (2001). Approaches to modular model development. *Agric. Syst.* **70**: 421-443.

Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT (2002). The DSSAT cropping system model. *European J. Agron*. (in press).

Katyal JC, Bijay-Singh, Vlek PLG, Craswell ET (1985). Fate and efficiency of nitrogen fertilizers applied to wetland rice II. Punjab, India. *Fert. Res.* **6**, 279-290.

Narang RS, Virmani SM (2001). Rice-wheat cropping systems of the Indo-Gangetic plain of India. Rice-Wheat Consortium Pap. Ser. 11. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India.

Simunek J, Sejina M, van Genuchten M Th (1999). The HYDRUS-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably-saturated media, version 2.0, U.S. Salinity Laboratory, USDA, ARS, Riverside, California. 227 pp.

Singh U, Timsina J, Godwin DC (2002). Testing and applications of CERES-rice and CERES-wheat models to rice-wheat cropping systems**.** Pages 17-32, In Humphreys, E, Timsina, J (Eds.), Modelling irrigated cropping systems, with special attention to rice-wheat sequences and raised bed planting". Proceedings of a workshop at CSIRO Land and Water, Griffith (Australia) 25-28 February 2002.

Spitters CJT, van Kuelen H, van kraalingen DWG (1989). A simple and universal crop growth simulator: SUCROS87. In: Rabbinge R, Ward SA, van Laar, HH (Eds.). Simulation and Systems Management in Crop Production. Simulation Monographs. Wageningen (Netherlands): Pudoc. Pp 147-181.

Thornton PK, Wilkens PW, Hoogenboom G, Jones JW (1994). Sequence Analyses User Guide. In: Tsuji GY, Uehara G, Balas S (Eds.), DSSAT 3.0. University of Hawaii, Honolulu, HI, USA. Pp. 67-136.

Timsina J, Connor DJ (2001). Productivity and management of rice-wheat systems: issues and challenges. *Field Crops Res*. **69**, 93-132.

Timsina J, Bouman BAM, Penning de Vries FWT, van Kraalingen DWG, Wan Harun WS (1994). Modeling tropical rice-wheat systems. In: Lansigan FP, Bouman BAM, van Laar HH (Eds), Proceedings of the SARP Applications Workshop: Agro-ecological Zonation and Characterization and Crop Rotation Optimization. IRRI, Los Banos, Philippines, pp. 58-70.

Timsina J, Singh U, Singh Y, Lansigan FP (1995). Addressing sustainability of rice-wheat systems: testing and application of CERES and SUCROS models. In: Fragile Lives in Fragile Ecosystems. Proc. Int. Rice Res. Conf. IRRI, Los Banos, Philippines, pp. 633-656.

Timsina J, Singh U, Singh Y (1996). Addressing sustainability of rice-wheat systems: analysis of long-term experimentation and simulation. In: Kropff MJ, Teng PS, Aggarwal PK, Bouma J, Bouman BAM, Jones JW, van Laar HH (Eds), Applications of Systems Approaches at the Field Level, Vol. 2. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 383-398.

Timsina J, Singh U, Badaruddin M, Meisner C (1998). Cultivar, nitrogen, and moisture effects on a rice-wheat sequence: experimentation and simulation. *Agron. J.* **90**, 119-130.

Timsina J, Godwin DC, Connor DJ (2000). Water management for mungbean within rice-wheat cropping systems of Bangladesh: a simulation study. CD-ROM Proceedings of the Third International Symposium on Systems Approaches for Agricultural Development (SAAD 3), 8-10 November 1999. Lima, Peru.

van Laar HH, Goudriaan J, van Keulen H (Eds) (1992). Simulation of crop growth for potential and water-limited production situations (as applied to spring wheat). Simulation Reports 27, CABO-TPE, Wageningen, The Netherlands. 72 pp.

White JW, Grace P, Fox PN, Rodriguez-Aguilar A, Corbett, JD (2000). Modelling the response of wheat yield potential to temperature- a global perspective. Pages 39-44, In: White JW, Grace PR (Eds), Modelling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batan, Mexico, 19-22 April 1999. NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

Wopereis MCS, Wosten JHM, ten Berge HFM, Woodhead T, de san Agustin EMA (1993). Comparing the performance of soil-water balance model using measured and calibrated hydraulic conductivity data: a case study for dryland rice. *Soil Sci.* **156**, 133-140.

Wopereis MCS, Bouman BAM, Tuong TP, ten Berge HFM, Kropff MJ (1996). ORYZA_W: rice growth model for irrigated and rainfed environments. SARP Research Proceedings. Wageneingen (Netherlands): IRRI/AB-DLO. 159 pp.

Yadav RL, Dwivedi BS, Pandey PS (2000). Rice-wheat cropping systems: assessment of sustainability under green manuring and chemical fertilizer inputs. *Field Crops Res*. **65**, 15-30.

Workshop recommendations and actions for the ACIAR project and the wider group

1. Mobilize groups to start putting together existing data for RW in the IGP, and for current rice varieties in southern NSW (plenty of data sets already for wheat in southern NSW)
Driver: Jagadish (Collaborators: PAU, CSIRO, NSW Agric., IRRI, Jaikirat)

2. Get existing models (DSSAT, APSIM, SWAGMAN Destiny) up and running for calibrations, validations and scenario analyses for flat layouts, for individual crops and for crop sequences. Some improvements in DSSAT, e.g. refinements of puddling, phenology routine in wheat and rice, cold routine in rice, irrigation switches for rice, rules for sequencing, etc., would be required. Sequencing capability needs to be added to Destiny.
Drivers: Jagadish, Emmanuel, Doug (Collaborators: Upendra, Bijay, Gajri, Arora, Michael)

3. Use HYDRUS-2D for comparative investigation (scoping) of water dynamics of bed geometries/soil characteristics (investigate drainage under various E and T scenarios).
Drivers: Emmanuel and Jagadish (Collaborators: Gajri, Arora)

4. Use FUSSIM2 to follow water and N dynamics—scoping study
Driver: Peter (Collaborators: Romy, Bas)

5. Evaluate the need to develop a spatial model based on the findings from 1-4 above, and experimental data comparing beds and flat experiments.

6. Maintain the network established at this workshop via distribution of the workshop proceedings, email updates on progress, and another joint meeting after 2-3 years.

7. Widen the network to others with similar interests (water saving in rice platform, IAEA CRP, NATP India, DSSAT/IBSNAT, GCTE, Wageningen, etc.)

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Appendix 1. Workshop Program (25-28 Feb. 2002)

Monday 25 Feb

11 am
- Welcome - John Blackwell, OIC CSIRO Land and Water, Griffith Laboratory
- Introductions
- Background to and purpose of workshop (Liz Humphreys)

11:20 am
- Rice-wheat cropping in IGP/Punjab - issues, future directions, soil, water and N mgt and dynamics (Bijay Singh and PK Gajri)
- ACIAR Project on permanent beds on a vertisol in Lombok, Indonesia (Jai Kirat Singh)

1:30-4:45
- Brief overviews on modelling approaches for rice and wheat
- DSSAT/CERES models (Upendra Singh)
- APSIM models (Michael Robertson)
- TRYM and maNage rice (Rob Williams/John Angus)
- SWAGMAN® Destiny (Doug Godwin/Emmanuel Xevi)

Tuesday 26 Feb

AM Modelling crop sequences - current and potential approaches, what's the state of the art, problems and issues, data requirements?
- Issues for crop sequences re carryover (Doug Godwin)
- Modelling sequences with APSIM (Merv Probert)
- DSSAT/CERES models (Upendra Singh)
- Potential for SWAGMAN Destiny to model sequences (Emmanuel Xevi)
- Discussion

PM -
- Visit bedfarming sites (Terry McFarlane)

Wednesday 27 Feb

AM Modelling bed geometries, especially for rice
- Impact of bed geometry on hydrology, implications for N transformations, possible modelling approaches (Doug Godwin)
- Hydrus 2D (Paul Hutchinson)
- FUSSIM2D model (Peter de Willigen)
- APSIM with multipoint/spatial capabilities (Merv Probert)
- Discussion - pro's and con's of various approaches

PM-
- Data collection – past, current and planned field experiments
- PAU and collaborators (Bijay Singh and PR Gajri)
- Rice on beds in Philippines and China (Romy Cabangnon)

Thursday 28 Feb

AM
- Where to from here?
- opportunities for synergies? complementarities? shared learning?
- how to facilitate - email chat group? 1:1? future get togethers?

Appendix 2. Participants

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