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Performance and application of CERES and SWAGMAN® Destiny models for rice-wheat cropping systems in Asia and Australia: a review

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Summary

Both rice and wheat are important crops in south Asia and Australia, and are grown together in sequence in large areas. The sustainability of rice-wheat cropping systems is a serious concern for food security in south Asia, and for viable regional communities in Australia. Issues facing both regions include reduced availability of water for irrigation, ability to farm profitably, and shallow watertables and salinity. Therefore there is much interest in technologies that increase water use efficiency, productivity and profitability of rice-based systems.

Crop models are useful tools for considering the complex interactions between a range of factors that affect crop performance, including weather, soil properties and management. Where pests and diseases are controlled, water and nitrogen fertilser management are the main factors influencing yield for a given environment. The CERES Rice and Wheat models simulate crop growth, development and yield taking into account the effects of weather, genetics, and soil water, carbon and nitrogen, and planting, irrigation and nitrogen fertilizer management. The rice and wheat models can also be run in sequence under the DSSAT framework. Therefore DSSAT/CERES Rice-Wheat offers the ability to evaluate options for increasing yield and water and nitrogen use efficiency of rice-wheat systems. However the CERES models do not simulate interactions with shallow groundwaters, and salinity dynamics and effects on crop performance.

SWAGMAN® Destiny is a lesser-known model developed by CSIRO Land and Water to enable simulation of growth and yield of a range of crops as they are affected by shallow groundwater, salinity and waterlogging, in addition to the more commonly modelled influences of weather, soil type, and management.

Before models can be applied with confidence, they need to be calibrated and validated for the varieties and environments of interest. This report reviews the results of calibration, evaluation and application of CERES Rice and CERES Wheat for rice-wheat cropping systems in Asia and Australia.

There are many reports of the evaluation and application of CERES Rice in tropical and subtropical Asia, and of CERES Wheat in temperate environments around the world. Most reports provide very little detail on determination of genetic coefficients, and the values used. Therefore genetic coefficients for commonly grown varieties of rice and wheat in the rice-wheat regions are not readily available. Where this information is available, genetic coefficients have generally been determined from only one study, thus results of validations may be impaired by poorly derived genetic coefficients. Further, it is difficult to identify reports of true validation (using independently derived genetic coefficients) as opposed to less rigorous evaluation (using genetic coefficients derived from the same data set).

CERES Rice has generally performed well in terms of number of days to key phenological events and grain and biomass yield in studies from tropical, sub-tropical and temperate Asia. However there are few reports of it's ability to predict a wider range of parameters, and evaluations under water and N limiting conditions are few and suggest that the model does not perform well under stress conditions. With increasing emphasis on improving water and N use efficiency, and the move away from continuously ponded rice culture in many regions, the performance of CERES Rice needs further evaluation under these conditions which attempt to save water and increase N use efficiency. The ability to simulate ammonium leaching needs to be included for the coarse textured soils of the rice-wheat region of northwest India, moreso with the current interest in moving away from puddled soils to alternative systems such as direct drilling and permanent beds. Evaluation of CERES Rice in the Australian rice-growing region has been limited, and demonstrates the need for a chilling injury routine to simulate the effect of low temperatures on fertility. Such a routine has been developed, but it requires further testing, and possible modification in the light of recent understanding of the mechanisms of cold damage.

CERES Wheat has been evaluated in a wide range of environments across the world, but only in a few cases in the sub-tropical environments of the rice-wheat areas of Asia. Evaluation in the sub-tropics has mostly been limited to phenology and grain and biomass yields, with reasonable ability to predict anthesis and maturity dates and grain yield, but not biomass yields. Results from other environments across the world have been mixed, reemphasising the importance of validating the model before applying (with refinements as required) it to the

environment of interest. Incorporation of processes simulating ammonia volatilisation could be important in evaluating irrigation and N fertiliser management on high pH soils such as those in the rice-wheat regions of northwest India.

While the ability of models to simulate the performance of individual crops is very important, it is also desirable to evaluate the performance of cropping systems over the medium and long term. There has been only one study evaluating the performance of the CERES Rice-Wheat sequence model under the DSSAT framework. In that study the sequential model performed fairly satisfactorily in terms of yield prediction, but simulation of soil C and N was not realistic. The DSSAT/CERES Rice-Wheat sequence model needs to be evaluated against observation from rice-wheat systems for a range of locations and management. The results of long-term experiments could be useful for this purpose, however adequate data availability is often a problem.

The CERES models offer other advantages, including routines for readily examining the impact of climate change and CO_2 levels, while the MERES model adds the ability to predict methane emissions to CERES Rice.

SWAGMAN® Destiny is a potentially useful model for identifying sustainable management in environments affected by shallow watertables and salinity. It has been evaluated against only a few data sets in Australia and one study in Asia, and there are no reports on its evaluation and application in highly regarded publications. Results to date suggest that it performs well in simulating wheat growth, yield and soil water content in the rice-growing areas of southern Australia, however it has not been tested for wheat in other environments, or for rice. At present SWAGMAN® Destiny can only simulate monocultures, and it’s usefulness will be greatly improved by incorporating the ability to simulate crop sequences.

There are many examples of the application of CERES Rice and CERES Wheat across Asia, but only a few applications for Australia. The models have been used most extensively in predicting the effect of various climate change scenarios on crop yields. Other major applications have included yield forecasting, yield gap and yield trend analysis, evaluating agronomic management strategies, evaluation of cropping options in new locations, prediction of greenhouse gas emissions, pest and disease management, and informing government planning. However, the impact of the application of the models on decision making by farmers and their advisors and policy makers is generally less clear.

1. Introduction

1.1. Rice-wheat cropping systems in Asia and Australia

Both rice and wheat are important crops in Asia. From 1992 to 2001 rice was grown on about 135 million hectares (Mha) and wheat on 100 Mha, producing approximately 518 and 246 million tonnes (Mt) per year of rice and wheat, respectively (FAO, 2002). Rice is grown in a range of ecosystems from tidal wetlands to rainfed and irrigated lowlands to highly disadvantaged and fragile uplands and mountains. Wheat was traditionally grown in cooler environments at high latitudes but is now also common in sub-tropical and tropical environments. Rice and wheat are also grown in annual sequences on about 13 Mha in the Indo-Gangetic Plains of south Asia and on about 13 Mha in China (Timsina and Connor, 2001). Rice-wheat cropping systems are critical to food security in Asia and also contribute to national revenue to varying degrees. Rice-wheat systems are fundamental to employment, income, and livelihoods for hundreds of millions of rural and urban poor of south Asia (Paroda et al., 1994; Timsina and Connor, 2001).

Wheat is the most important crop in Australia and is grown on approximately 10.4 Mha, with average production of 19.1 Mt/yr (FAO, 2002). Wheat is predominantly grown as a rainfed crop, but is also an important crop in irrigation areas, especially in the rice growing areas. From 1992 to 2001 rice was grown on an average of 0.13 Mha in southern NSW, producing 1-1.7 Mt of paddy annually. Rice is the dominant broadacre crop in the irrigation areas of southern NSW, occupying 10-25% of the landscape for about 7 months. The rice industry is important for the viability of regional communities and for export earnings, as the majority of the crop is exported and value added (Linnegar and Woodside, 2003). Irrigated wheat is often grown in rotation with rice, either immediately after harvest, or after 12 months fallow.

Food security in south Asia is now threatened by yield stagnation, and possibly decline in rice yields, in the face of continuing population growth (Ladha et al., 2003). Added to this are current threats to sustainability including overexploitation of ground and surface waters, waterlogging and salinity, declining soil organic matter, water and atmospheric pollution, and global climate change (Hobbs and Gupta, 2003). The sustainability of irrigated agriculture in the rice-growing areas of southern Australia is also threatened by reduced availability and the increasing price of water (Humphreys and Robinson, 2002), and by secondary salinisation (van der Lely, 1993, 1998) and global climate change.

A range of technologies have been identified in recent years which have the potential to increase resource use efficiency, reduce adverse environmental impacts, and increase the productivity and crop diversity of rice-based cropping systems in Asia and Australia (Beecher et al., 2003; Hobbs and Gupta, 2003). We hypothesise that evaluation and site-specific adaptation of these technologies can be assisted through the application of crop simulation models.

1.2. The role for crop models

Agricultural systems are complex, and understanding this complexity requires systematic research, but resources for agricultural research are shrinking. Field experimentation can only be used to investigate a very limited number of variables under a few site-specific conditions. Crop models are useful tools for integrating knowledge of the bio-physical processes governing the plant-soil-atmosphere system, and for extrapolating research results to other locations or sites. Where long sequences of daily weather data, crop models can be used to evaluate the production uncertainties associated with these management scenarios. Models can thus be used to extend research results both spatially and temporally. Matthews and Stephens (2002) discussed the applications of crop-soil simulation models in developing countries, and assigned the main applications into three categories: research, decision support, and education and training. Examples of these applications are provided in section 10.

There are many crop growth simulation models. Some are more generic in nature while others are built for specific purposes. Most of these models simulate crop growth and soil processes using daily time steps. All models are developed with some assumptions and hypotheses, and all have strengths, weaknesses and limitations for appropriate application. Well-known crop modelling groups across the world include IBSNAT/IFDC (International Benchmark Sites Network for Agrotechnology Transfer/International Fertilizer Development Centre) in USA, WAU/AB-DLO (Wageningen Agriculture University/Centre for Agrobiological Research) in the Netherlands, and APSRU (Agriculture Production Systems Research Unit) in Australia. The IBSNAT project was initiated in 1982, and over the past 20 years it has developed more than 15 models, including CERES (Crop estimation through resource and environment synthesis) Rice and CERES Wheat, which are available either as stand-alone models or within the DSSAT (Decision Support System for Agrotechnology Transfer) shell (Uehara and Tsuji, 1993). All the DSSAT models are continuously being refined, calibrated, validated, and applied across the world by the scientists who developed the models and their collaborators and others. The Wageningen Group is probably the strongest modelling group in the world in terms of concentration and strength of modelers and the range of models being developed. Most of the models that are available today across the world have some sort of origin from Wageningen. WAU/AB-DLO also has projects and collaborators, mostly in Asia and south America, the most notable being the SARP (Simulation and Systems Analysis for Rice Production) project with IRRI and collaborators in Asian countries (ten Berge, 1993) and the REPOSA (Research Programme On Sustainability in Agriculture) project in Costa Rica (Jansen, 2001). The APSRU group has developed and applied APSIM (Agriculture Production Systems SIMulator) with a range of models initially targeted for rainfed cropping, but also applicable to irrigated conditions. All these modelling groups are networked within the ICASA (International Consortium for Agricultural Systems Analysis) network. While all these groups have developed several models, it has been suggested that the DSSAT models have had the biggest impacts in developing countries in terms of their applicability, diffusion, and adoption (Mathews and Stephens, 2002). SWAGMAN® (Salt, Water, and Groundwater MANagement) Destiny, a lesser-known model, was developed by CSIRO Land and Water to enable simulation of growth and yield of a range of crops as they are affected by shallow groundwater, salinity and waterlogging, in addition to the more commonly modelled influences of weather, soil type, and management (Godwin et al. 2002).

To confidently and effectively make use of models, they need to be calibrated and validated in the environments where they are to be applied. This review examines the performance and application of the CERES Rice, CERES Wheat and SWAGMAN® Destiny models for rice-wheat systems within Asia and Australia.

1.3. Why CERES and SWAGMAN® Destiny models?

Modelling rice-wheat sequences requires crop models that can describe the dynamic and at times extreme changes in hydrological conditions, and their profound impact on N dynamics. During the rice phase, soils are often continuously flooded and much of the soil becomes anaerobic. In continuously flooded rice culture, the most common limitations to rice crops realizing their genetic potential include solar radiation, temperature, nutrition, pests and diseases. Where pests and diseases are controlled, N is often the most limiting factor that can be managed. In areas where water is not continuously available, intermittent inundation will occur with associated periods of aerobic and anaerobic soil conditions. These changes in aeration status of the soil can have large consequences for nutrient (mainly N and P) transformations, transport and availability to rice crop.

Nitrogen behaves very differently in flooded anaerobic soil than in non-ponded aerobic conditions. For example, in ponded conditions, the movement of nitrate, urea and ammonium between the soil and floodwater is important, and ammonia volatilisation from the floodwater can be a major source of N loss. When rice soils are drained or become aerobic, ammonium is rapidly nitrified. Subsequent rewetting of the soil will lead to denitrification of the nitrate produced during the drained period. These cycles of nitrification and denitrification are often major sources of loss of N from rice cropping systems. During the transition between rice and wheat phases in rice-wheat cropping systems, soils will again go through a phase change from anaerobic to aerobic conditions. CERES Rice is able to simulate detailed soil and water N dynamics under changing hydrological conditions.

The DSSAT framework provides a facility for simulating crop sequences, including rice-wheat using the CERES Rice and Wheat models. The CERES Rice and Wheat models have been widely tested and applied in rice-wheat regions. However, the CERES models do not simulate the impact of waterlogging and salinity on crop performance, whereas SWAGMAN® Destiny provides this capability, but without the detailed N dynamics of CERES Rice and Wheat.

This report reviews the performance of CERES Rice, CERES Wheat and SWAGMAN® Destiny in rice-wheat regions, and to document the range of applications for which they have been used. Comparisons with other models are also included where these have been reported.

2. Brief model description

The CERES models simulate crop growth, development and yield taking into account the effects of weather, management, genetics, and soil water, C and N. The minimum data requirements for operation, calibration and validation of the rice and wheat models, for crops grown singly or in sequence, are provided by Hunt and Boote (1994) (Table 1). The model processes of CERES Rice and CERES Wheat have been incompletely documented in a fragmented way in various publications. Since the focus of this Report is on performance and applications of these models, only the main features of model components and processes are described here. The DSSAT models, including CERES Rice and Wheat, are however readily available for purchase from the DSSAT Group.

2.1. Official versions of CERES Rice and CERES Wheat

2.1.1. Phenology

The phenology components of CERES Wheat and CERES Rice have been described by Ritchie and NeSmith (1991), Singh (1994) and Ritchie et al. (1998). The models describe the progress through the crop life cycle using degree-day accumulation (heat sum). The duration of growth stages in response to temperature and photoperiod varies between species and cultivars, and genetic coefficients are used as model inputs to describe these differences (Table 2; Hunt and Boote, 1994; Singh et al., 2002). In wheat, the duration from emergence to terminal spikelet formation is influenced by the vernalization (chilling) requirement and photoperiod. In rice, a developmental phase (juvenile stage) occurs when the crop is not sensitive to photoperiod. After this stage sensitivity to both photoperiod and temperature determine the time to panicle initiation.

The phenology component also simulates the effect of water or N deficit on the 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 the beginning of grain filling.

2.1.2. 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 which is modified by water deficit and N deficiency stress indices. Leaf area expansion depends on leaf appearance rate, photosynthesis and specific leaf area. Leaf area expansion is quite 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 cultivar specific coefficients.

2.1.3. Water balance

The soil water balance model initially developed for CERES Wheat is used in 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. The soil has parameters that describe its surface condition and layer-by-layer soil water holding and conductivity characteristics. The model uses an overflow or “cascading bucket” approach for computing soil water drainage when a layer’s water content is above the drained upper limit. This has been misleadingly referred to as a “tipping bucket” approach in the past (a tipping bucket completely empties once the “fill” point is reached).

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 a layer is less than the computed vertical drainage, actual drainage is limited to the conductivity value, and water accumulates above the layer. This feature allows the model to simulate poorly drained soils and perched water tables.

CERES Rice can also simulate the effect of bund height. Floodwater depth, runoff (when floodwater depth exceeds bund height) and evaporation from floodwater are simulated. The model also simulates the effect of puddling on percolation rate and bulk density, temporal changes in these properties, 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 coarse textured soils such as those of north west India.

2.1.4. Soil organic mater and N dynamics

The most recent version of the DSSAT models (v.4.0) has two options to simulate the soil organic matter (SOM) pools and dynamics: (1) the original SOM model used in DSSAT v3.5 (Godwin and Jones, 1991; Godwin and Singh, 1998), and (2) the SOM module developed by Gijsman et al. (2002), based on the CENTURY model (Parton et al., 1988, 1994). The CENTURY-based module divides the SOM into more fractions, each of which has a variable C:N ratio and can mineralize or immobilize nutrients. 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). The SOM decomposition rate and residue flows also vary with soil texture.

The N module of CERES Rice simulates hydrolysis of urea, nitrification, ammonia volatilization, nitrate leaching, denitrification, algal activity and floodwater pH changes, plant N uptake and partitioning under continuously flooded, intermittently flooded and non-ponded conditions (Singh, 1994). The floodwater N chemistry component of the model (Godwin et al., 1990; Godwin and Singh, 1991, 1998) uses an hourly time step to calculate rapid N transformations and to update soil-floodwater-atmosphere equilibria. CERES Rice, however, does not simulate ammonium leaching, which can be important on coarse textured soils (Katyal et al., 1985). CERES Wheat cannot simulate ammonia volatilization loss from irrigated wheat fields, which could be substantial on calcareous soils. Incorporation of these processes into the rice and wheat models, respectively, would assist evaluation of N management options in rice-wheat systems (Timsina et al., 2002).

2.2. Modifications of CERES models

Many researchers have modified the source code of the CERES models to improve or add processes relevant to their applications, or to build new models. These modifications are not provided with the official versions of DSSAT, and the code is held by the developers of the modifications.

2.2.1. Methane emissions from rice fields

Mathews et al. (2000a) developed the MERES (Methane Emissions from Rice Ecosystems) model for predicting methane emissions from rice fields. They incorporated a subroutine describing the effect of alternative electron acceptors on production of methane into CERES Rice and linked it to the model of Arah and Kirk (2000) describing the interaction between methane and oxygen in the soil. The performance of MERES is discussed in section 4.5

2.2.2. Tillage

The DSSAT models account for residue incorporation and its effects on soil C and N balances. They don't, however, simulate the effects of surface residue on important soil physical properties affected by tillage and residue management such as bulk density, hydraulic conductivity, soil temperature, evaporation and infiltration. Nonetheless, CERES Wheat, simulated the effects of four tillage practices (conventional mouldboard ploughing, ripper subsoiling, surface disc harrowing, minimum tillage with rotary hoeing) on soil water content in various layers fairly well, but not grain yield in southern Italy (Castrignano et al., 1997). Dadoun (1993) developed a tillage routine, CERES-Till, to predict the influence of crop residue cover and tillage on soil surface properties and plant development. Andales et al. (2000) adapted CERES-Till, incorporated it into the CROPGRO-Soybean model, and tested it in central and northwest Iowa. Predictions of changes in surface residue on bulk density, hydraulic conductivity, runoff curve number, and surface albedo were consistent with expected behaviours of these parameters. The tillage model showed differences in runoff and soil evaporation between the mouldboard, chisel plow, and no-till treatments. It correctly predicted cooler soil temperatures under no-till in early spring and delayed emergence with surface residues. It also correctly predicted differences in soybean yield based on the effects of surface residue (delayed emergence, increased rainfall interception, and reduced soil evaporation) on soil properties (runoff curve number, bulk density, saturated hydraulic conductivity).

2.2.3. Salinity

Castrignano et al. (1998) incorporated salinity effects in CERES Maize by modifying the potential evapotranspiration subroutine and by developing a salinity stress index in the water uptake subroutine. The salinity stress index was determined as a function of pre-dawn leaf water potential, and was designed to simulate crop response to irrigation with saline water in Mediterranean conditions. The model performed well for final grain yield but it tended to underestimate (~8%) above-ground biomass and maximum leaf area index and either under or overestimated the evapotranspiration (ET) in Italy. They concluded that the model needs improvement in: (1) increasing its sensitivity to soil type, (2) redefining the stress functions, and (3) modifying the simulation of the rate processes of leaf growth and senescence.

2.2.4. Cold damage

Rice in the temperate environment of southern NSW, Australia, suffers from cold injury due to low night temperatures during the early pollen microspore stage. Godwin et al. (1994) developed and incorporated a routine into CERES Rice to predict the effect of chilling injury on rice yield. The model computes minimum and maximum floodwater temperatures from minimum and maximum ambient temperatures and floodwater depth. It also considers the duration of the chilling sensitive period and threshold temperatures, and calculates the chilling index using a critical temperature which is a characteristic for a given variety. The performance of CERES Rice v.2.1.C is discussed in section 4.6.

2.2.5. The APSIM wheat model

The Agriculture Production System Simulator (APSIM) Shell includes a wheat model which was developed from a combination of the approaches used in the N-Wheat and I-WHEAT models. The N-Wheat module was derived from CERES Wheat (Robertson and Lisson, 2002). Likewise, APSIM Maize was based on CERES Maize.

2.3. SWAGMAN Destiny

2.3.1. Overview

SWAGMAN® Destiny simulates crop growth and yield in response to shallow watertable levels, root zone salinity, available soil water, waterlogging and prevailing weather conditions. It enables strategies to be formulated that maximise productivity while managing watertables and avoiding salinisation. With long-term weather data, different sequences of simulations can be used to assess a particular strategy by probabilistic analysis. The minimum data set requirements for SWAGMAN® Destiny are presented in Table 3.

2.3.2. 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 determines the layers most favourable for root growth. Stresses due to water shortage, low aeration (waterlogging), salinity and N deficit 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 accumulated is reduced by the prevailing stresses. Zero-to-unity stress indices are calculated during each day of simulation for soil water deficit, salinity, N deficit and aeration. The most limiting of these stress indices is used to scale each day's potential growth.

2.3.3. 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 developed for Destiny have been included in the most recent versions of the CERES models. The water balance model simulates infiltration, 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. Detailed descriptions of the model can be found in Godwin et al. (2003).

The model uses a daily time step and simulates the 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, piezometric pressure heads and fluxes at a plane 5 m deep are used as inputs to the model. Depending on the pressure heads 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.

3. Calibration of CERES Rice and CERES Wheat

Model calibration or parameterization is the adjustment of parameters so that simulated values compare well with observed values. The genetic coefficients that influence the occurrence of developmental stages in the CERES models can be derived iteratively, by manipulating the relevant coefficients to achieve the best possible match between the simulated and observed number of days to the phenological events. Other coefficients can be derived from determinations of non-limited grain weight, number of grains per panicle (rice) and rate of grain filling (wheat). Alternatively, genetic coefficients can be determined using the GENCALC software that uses the observations of phenological events from one or several experiments from a range of environments (Hunt and Pararajasingham, 1994). The DSSAT shell includes default genetic coefficients for a range of species and cultivars, and the model user can also develop estimated coefficients for local conditions from the default coefficients. Many commonly grown cultivars are not included in the DSSAT shell, many of the cultivars that are included are not commonly grown, and the source of the genetic coefficients is not provided. The DSSAT shell contains genetic coefficients for very few varieties of rice and wheat grown in rice-wheat areas of Asia and Australia.

The few genetic coefficients of rice that are reported in the literature are summarized in Table 4. All reported genetic coefficients from Asia are for Indica varieties, while the two from Australia are for Japonicas, one of which (Calrose) is a tall variety which is no longer grown. Generally, data sets collected from previous agronomic research are lacking in some of the key observations required for calibrating process-based crop growth models. CERES Rice has been widely evaluated and used across Asia and Australia, however most studies do not describe how the genetic coefficients were derived nor the values used. Moreover, many reports do not even provide the cultivar names or the observed number of days to phenological events, making it difficult to calculate or assign coefficients. Many studies do not report the version of CERES Rice used. Only Mall and Aggarwal (2002) used data from more than one site or climate to derive genetic coefficients.

Reports detailing the calibration of CERES Wheat are also limited to a few cultivars. The coefficients for spring wheat reported from studies in Asia and Australia are summarized in Table 5. The coefficients for RR21 derived from separate studies in India and Nepal were very similar (Timsina et al. 1995, 1997), but there were differences in the values of coefficients for HD2329 derived by Hundal and Kaur (1997) and Pathak et al. (2003) using CERES Wheat v.2 and v.3.5, respectively. One reason for the differences could be due to the use of different versions of CERES Wheat. In Australia, Smith et al. (2003) derived coefficients for three wheat cultivars, Janz, Yecora, and Bindawarra. As for rice, most of reported genetic coefficients are derived from results of a single site, soil, and weather conditions.

4. Evaluation of CERES Rice

Validation is the comparison of the results of model simulations with observations from crops that were not used for the calibration. A model should be rigorously validated under widely differing environmental conditions to evaluate the performance of major processes in addition to its ability to predict yield. CERES Rice has been validated and evaluated for many locations across the rice-growing regions in Asia and Australia. The results are presented in Tables 6 and 7 and Figures 1, 2, and 3.

4.1. Phenology

The ability of CERES Rice to predict the duration of key phenological events has been examined in many studies (Table 5 and Figure 1). In tropical Asia, validation of CERES Rice was first reported by Alocilja and Ritchie (1991) for three upland rice cultivars (IR 43, UPLRi 5, UPLRi 7) in six experiments in the Philippines. Agreement between observed and predicted values was good, with differences of only 0 to 4 days. at three sites in Bangkok, Thailand. Tongyai (1994) reported that the simulated number of days to physiological maturity was overestimated by 8 to 16 days. In north and north east Thailand, Jintrawat (1995) evaluated CERES Rice (v.2) for both photoperiod sensitive and insensitive cultivars against two years of data for six sites, and found accurate model predictions of phenology for photoperiod insensitive cultivars, but for a photoperiod sensitive cultivar the heading dates were underestimated, especially for early planting dates. The author attributed this primarily to N shortage, but more importantly, it was due to the inability of v.2 of the model to simulate the growth and phenology of photoperiod sensitive cultivars. The ability to simulate growth and phenology of photoperiod sensitive cultivars is included in more recent versions of CERES Rice. More recently, CERES Rice accurately predicted the maturity of the photoperiod sensitive cultivar KDML 105 at six sites in northeast Thailand (Boonjung, 2000). However, the number of days to panicle initiation and anthesis was overestimated, but Boonjung (2000) did not indicate by how many days, nor possible reasons for overestimation.

CERES Rice phenology has been evaluated in sub-tropical locations such as India and Bangladesh. Using data sets from several experiments at Pantnagar, northwest India, Timsina et al. (1995) found that CERES Rice predicted the number of days to anthesis of Pant-4 cultivar to within four days for 4 out of 10 treatments, while predictions were underestimated by 5-14 days in 6 treatments. The number of days to maturity was within 4 days in 4 out of 12 treatments and over or under-estimated by 5 to 14 days for 8 treatments. In Kerala, south India, the predictions were better with simulated anthesis dates of Jaya and IR48 within 4 days and maturity dates within 2 days of observed dates (Saseendran et al., 1998a,b). In northern Bangladesh, there was almost perfect agreement between the predicted and observed number of days to maturity of BR11 and BR14, although the predicted number of days to anthesis was 4 to 7 days earlier than the observed number of days (Timsina et al., 1998).

At temperate and sub-tropical climate locations in northern and southwestern Japan, the predicted number of days to physiological maturity of unspecificed cultivars was within –2.8 to +2.1 days of observations (Seino, 1995).

The ability of CERES Rice to predict phenology has also been compared with other models. For example, Mall and Aggarwal (2002) compared the performance of CERES Rice and ORYZA1N and reported that both models predicted the number of days to flowering reasonably well for 11 locations from north to south India, including four locations in northwest India (Delhi, Pantnagar, Ludhiana, and Kapurthala). The observed duration from sowing to flowering varied from 37 (Coimbatore) to 85 (Pantnagar) days whereas the simulated duration varied from 36 (Coimbatore) to 85 (Pantnagar) days for CERES Rice, and 43 (Coimbatore) to 78 (Pantnagar) days for ORYZA1N. Most of the simulated values were within 15% of observations for both models, but CERES Rice simulated flowering duration with less error (RMSE=4.5 d) than ORYZA1N (RMSE=4.8 d). Likewise, Salam et al. (2003) compared observed and predicted values for six rice growth models (CERES Rice, ORYZA1, ORYZA-European, RICAM, SIMRIW and TRYM) in four diverse rice-growing environments in Asia (early and late sowing at Nan Chang, southern China; Moroika, northern Japan; and dry season at Los Banos, Philippines), for 10 years of observations at each site. Model predictions for four traits (growth duration, grain yield, above ground biomass, and harvest index) were compared with observations using mean squared deviation (MSD) and its three additive components. Across the four data sets and 10 years, the MSD for growth duration ranged from 87 to 238**.** CERES Rice, RICAM, SIMRIW and TRYM had the smallest MSDs. All models simulated the growth duration well at Nan Chang for early and late sowing, whereas the simulated duration deviated more for Moroika and Los Banos.

Figure 1 presents the results of the evaluation of CERES Rice for predicting the number of days to anthesis and maturity. The results show reasonable agreement between simulated and observed days to anthesis and to maturity (RMSE = 4.8 d and SE = 4.4 and 4.6 d, respectively, for anthesis and maturity) for a range of varieties across tropical, sub-tropical and temperate environments. The figure does not include data from the two studies (Tongyai, 1994; Jintrawat, 1995) in Thailand which used photoperiod sensitive varieties with CERES v.2.

4.2. Grain and biomass yields, and yield components

Validation of CERES Rice for grain and straw yields and yield components has been reported for several field studies across Asia (Tables 6 and 7; Figure 2). The first report was by Godwin et al. (1990), who compared the predicted grain and biomass yields against data from field experiments at several sites in the Philippines (Buresh et al., 1988a,b; John et al., 1989a,b). In most cases, there was a good agreement between predicted and observed values, with R^2 of 0.65 and 0.67, respectively, for grain and biomass yields.

Although, as discussed above, CERES Rice did not always accurately predict the date of phenological events in Thailand, it predicted grain yield quite well. For example, Tongyai (1994) reported a fairly good agreement between simulated and observed grain and biomass yields for 3 sites over 3 years in Bangkok. Grain yields were overestimated by 0.2 to 0.4 t/ha (4.5-9%) and biomass was underestimated by 0.8 to 1.0 t/ha (10-12%). In central, north and northeast Thailand, CERES Rice predicted grain weight, grain number, and grain yield of both photoperiod sensitive and insensitive cultivars reasonably well (Jintrawat, 1995). Grain weight was predicted within 0-3%, grain number/m^2 within 15-50%, and grain yield within 15-20% of observed values. Boonjung (2000) also reported good agreement between observed and predicted yields of the photoperiod sensitive cultivar KDML (R^2=0.70) in the northeast Thailand. In Indonesia, Amien et al. (1996) reported that CERES Rice (v.3) underpredicted grain weight by 1 mg resulting in underprediction of yields by 10-20% at all locations, except Sukamandi in west Java. Observed grain yields across locations ranged from 2.65 t/ha to 7.85 t/ha while the simulated yields ranged from 2.65 to 7.0 t/ha, with R^2 of 0.87. In East Java, they reported a grain yield of 5.1 t/ha with 250 kg of urea/ha compared with 5.8 t/ha from the simulation. Using MERES, Mathews et al. (2000b) reported good agreements between simulated and observed grain yields at Los Banos, Philippines and Hangzhou, China, except for three treatments in the dry season at IRRI with mid-season drainage.

In the sub-tropical environment of Kerala, India, Saseendran et al. (1998a,b) reported that grain yields of Jaya and IR8 were within 3% and straw yields within 27% of measured yields, and that grain weight and grain number per m^2 were also predicted closely. In the same state, Rao et al. (2002) also observed very good agreement between simulated and observed yields of Jaya, Jyothi, and Triveni for all transplanting dates in one year (0-2% of observed values). In a year in which heavy rains which caused high sterility, the simulated yields were 5-10% greater than the observed yields. Timsina et al. (1995) reported that for many experiments at Pantnagar in northwest India, simulated grain yields of Pant-4 were generally within 1-15% of observed yields, but in some cases, the simulated yields were out by up to 40%, mainly due to the fact that the model didn't accurately predict the phenological events. In northern Bangladesh, simulated yields of BR14 and BR11 were either over or underestimated relative to observed yields, which was reflected in the high RMSE of 1.3 t/ha. The model undoubtedly underestimated yields at zero N (Timsina et al., 1998). However, some of the discrepancy between simulated and observed yields was due to insect damage and lodging at high N rates, which resulted in lower yields.

Seino (1995) compared the simulated and measured grain yields for three sites (Miyagi and Niigata in the north) and Miyazaki in the south) in temperate Japan. At all sites, simulated grain yields were within 0-5% of observed yields. In temperate southern Australia, predicted yield of Amaroo grown in 1989/90 was within 10% of the measured yield of 9.6 t/ha, however, there were large discrepancies between the yields of experiments from other years and yields simulated by CERES Rice v.2.1 due to sterility induced by cold damage, which is not simulated in official versions of CERES Rice (section 4.6; Godwin et al., 1994; Meyer et al., 1994).

Bachelet et al. (1993) compared observed rice yields with yields predicted by CERES Rice and MACROS (Modules of Annual Crop Growth Simulator) (Penning de Vries et al., 1989) under various temperature regimes. Without calibration (using default coefficients), grain yield predictions by both models were fairly reliable, although the fit of observed to predicted values was closer for MACROS than CERES. Kropff et al. (1994) compared predicted yield potential for four rice models (ORYZA1, CERES Rice, SIMRIW, and TRYM) in four environments (dry and wet season crops at IRRI/Philippines, Kyoto/Japan, and Yanco/Australia). All models simulated the wide range in total biomass accumulation and yield relatively accurately. However, all models overestimated yield in the wet season at IRRI and, with the exception of ORYZA1, all models predicted LAI inaccurately. Mall and Aggarwal (2002) concluded that both CERES Rice and ORYZA1N predicted grain yield satisfactorily (within ±15%), especially for yields above 4 t/ha, and accuracy of prediction of grain and biomass yields was similar for ORYZA1N (RMSE=0.6 t/ha) and CERES Rice (RMSE=0.7 t/ha). Both models also predicted grain number fairly accurately over the range 15,000-32,000 grains/m^2. The authors concluded that both models were unable to adequately simulate crop growth and yield when there are stresses such as low N and water deficit. At lower yield levels, ORYZA1N performed better than CERES Rice, whereas the reverse was true at higher yields.

Salam et al. (2003) found that CERES Rice, ORYZA1, ORYZA-European, RICAM, SIMRIW and TRYM all closely predicted the Moroika and Nan Chang early sowing yields, but gave large deviations for late sowing at Nan Chang and the dry season at Los Banos. The largest deviations occurred with SIMRIW and ORYZA1, followed in order by TRYM, CERES Rice, ORYZA-European, and RICAM. CERES Rice and RICAM had the highest and lowest deviations for biomass, respectively, although the difference between models was much less than for grain yield. For harvest index, the largest deviation was from RICAM and the smallest with TRYM. RICAM and ORYZA1 had the largest MSD for Nan Chang early and late seasons, while CERES Rice had the largest MSD in Moroika.

Observed and predicted yields and final biomass from the studies reported in Tables 6 and 7 are shown in Figure 2. The data for yields affected by cold damage are not included (Meyer et al., 1994; Godwin et al., 1994). The results show that agreement between observed and predicted yields and final biomass was not very satisfactory (RMSE=1.55 and 13.1 t/ha, SE=1.44 and 2.94 t/ha, and R^2=0.38 and 0.25 respectively, for grain and biomass yields), suggesting that growth and biomass routines need to be revisited and refined, and/or deficiencies in the data sets.

4.3. Growth

There are only a few published reports on the performance of CERES Rice in predicting the time course production of biomass and leaf area. Mall and Aggarwal (2002) concluded that there was a good agreement between the measured and simulated values (using CERES Rice and ORYZA1N) for the general pattern of LAI over the growing season, however both models underpredicted peak LAI, and the authors attributed this to limited calibration and initialization of the models. CERES Rice simulated LAI at different growth stages slightly better than the ORYZA1N in all treatments. Meyer et al. (1994) also observed that CERES Rice v.2.1 underestimated peak LAI considerably, although it predicted the time of complete canopy closer (LAI ~3) reasonably accurately. The predicted panicle density was also greatly under-predicted. Salam et al. (2001) developed nursery growth and transplanting shock routines using data from Bangladesh and incorporated them into CERES Rice. Without the new routine the model overestimated root and leaf dry matter and underestimated culm dry matter during the 30-d period of seedling growth, and overestimated the duration of the period of transplanting shock. With the new routine, the seedling growth and transplanting shock periods were simulated well. However, the response to transplanting shock was not simulated well. Using MERES, Mathews et al. (2000b) found good agreement between observed and predicted total above and below-ground biomass in the Philippines and China for all treatments except those with midseason drainage.

4.4. Crop and soil N

Buresh et al. (1991) tested the grain yield sensitivity of CERES Rice to some soil and management factors, and reported that the model was responsive to increased above and below-ground residue inputs, initial soil ammonium, and rate of mineralization.

Godwin et al. (1990) and Buresh et al. (1991) compared predicted crop N uptake and ammonia loss from urea in eight irrigated lowland rice experiments, with observed N uptake and N losses determined from ^{15}N balance, at three sites in the Philippines. The experiments involved a range of water management treatments from continuous flooding to alternate wetting and drying. Predicted N uptake was usually slightly overestimated, but overall, the performance of model was satisfactory. In most cases and, more particularly in continuously-flooded soil with low percolation rates (<0.2 cm/d), the model predicted negligible denitrification loss, which was consistent with field measurements (Buresh and de Datta, 1990). In alternative wetting and drying treatments, however, water deficit during the vegetative growth phase increased predicted N loss, particularly by nitrification-denitrification from both fertilizer and soil N. Thus the predicted N loss exceeded the losses calculated from ^{15}N balance due to overprediction of soil drying during periods of water deficit, insufficient lag time for the onset of nitrification following the onset of soil drying, and overestimation of the denitrification rate upon reflooding. In one study in southern Australia total biomass and N uptake predicted using CERES v.2.1 was within 3% of observed value, however the partitioning of N between straw and grain was inaccurate (Meyer et al., 1994).

The data for total crop N uptake in Figure 3 come from several treatments/experiments in Meyer et al. (1994) and Timsina et al. (1998). Observed N uptake in Meyer et al. (1994) ranged from 33.7 to 205.2 while the simulated N uptake ranged from 89.2 to 249 kg/ha. In Timsina et al. (1998) the observed and simulated N uptake both ranged from 48-175 kg/ha, with an RMSE of 17 kg N /ha. Though some treatments in Meyer et al. (1994) were affected by cold damage and high-N treatments in Timsina et al. (1998) were affected by lodging and insect damage, Figure 3 undoubtedly reveals that CERES Rice did not predict N uptake satisfactorily in the subtropical Bangladesh climate and in temperate Australia. Results suggest that the codes related to N uptake in CERES Rice need to be reexamined and reevaluated to improve its performance in terms of N uptake.

4.5. Methane emissions and evapotranspiration

Using MERES, Mathews et al. (2000b) observed good agreement between simulated and observed seasonal patterns and quantities of methane emission from rice straw and green manure treatments for a dry season crop at IRRI. In the rice straw treatment the model slightly overpredicted the plume of methane at the second drainage just before harvest. MERES also accurately predicted the seasonal methane emissions at Maligaya, Philippines, and Hangzhou, China. Mathews et al. (2000b) tested the grain yield sensitivity of MERES to a range of parameters. MERES was sensitive to root death coefficient, specific root exudation rate, root transmissivity, green manure addition, initial size of oxidized alternative electron acceptor pool, seasonal temperature, crop duration, floodwater depth, length of drainage period, type of organic amendments, phosphogypsum, and percolation rate.

In temperate Australia, the pattern of observed evapotranspiration closely matched predicted values using CERES Rice v.2.1 over the whole season, and total evapotranspiration was within 2% of the measured value of 1062 mm (Meyer et al., 1994).

4.6. Cold damage

Meyer et al. (1994) monitored a commercial rice crop near Griffith to validate CERES Rice (v.2.1), and derived genetic coefficients for Amaroo, based on which, they also derived coefficients for Calrose (Table 4). When the model was tested against data from several experiments over several years, there were large discrepancies between simulated and observed yields due to the effect of low temperatures on floret sterility. Godwin et al. (1994) developed a chilling injury routine and evaluated the performance of v.2.1 with the chilling injury routine (v.2.1C) for rice grown under sprinkler irrigation and continuous flood (CF) near Griffith, in a year when there was considerable cold injury (Muirhead et al., 1989). The model without the chilling injury routine simulated grain yield satisfactorily for CF at high N rates (80 and 120 kg/ha), but substantially underestimated yield for the zero N rate, and overestimated yields for all the sprinkler irrigation treatments at all N rates. With the chilling injury routine, simulated grain yields on all sprinkler treatments were similar to the observed yields (Godwin et al., 1994). The difference in response to the sprinkler and CF treatments between v.2.1 and v.2.1C was due to the presence of floodwater on CF. Floodwater raised the simulated plant temperature sufficiently to enable it to escape the bulk of chilling injury, whereas the sprinkler treatments (with no floodwater) were severely affected by chilling injury. The mitigating effects of floodwater depth on temperature, chilling injury and yield and its interaction with N fertility are well documented (Lewin and Heenan, 1987; Williams and Angus, 1994). The model with chilling injury also satisfactorily simulated the grain yields from other experiments near Griffith (Humphreys et al., 1987), thus capturing the differences in N response due to chilling injury. The chilling routine needs to be refined, taking into account new understanding of the mechanisms of cold damage, and tested in the latest version of CERES Rice for current varieties under a range of seasonal conditions and water regimes.

4.7. Conclusions on the evaluation of CERES Rice

Although CERES Rice has performed well against data sets from many of the rice-growing areas in Asia, it has also not performed satisfactorily in many other studies. The discrepancies in predictions of phenological events and grain yield were partly due to insufficient data for derivation of genetic coefficients and partly to the inability of the model to perform well when the crop is under considerable stress (low N and water deficit). New resource conserving technologies involve more rationing of water and N, therefore careful evaluation under these conditions is required. Better evidence of the ability of CERES Rice to simulate a range of important parameters other than yield is also required, including the time course production of biomass, leaf area, N uptake, and soil water and mineral N dynamics.

5. Evaluation of CERES Wheat

Compared to CERES Rice, there are few reports of validation or evaluation of CERES Wheat in Asia, although there are many reports of its validation and evaluation in many other parts of the world including north and south America, Europe, Africa and Australia. In Asia, the model has been validated for only a few locations in Japan, Bangladesh, and India (Table 8; Figures 4 and 5).

5.1. Phenology

In sub-tropical northern Bangladesh, Timsina et al. (1998) reported reasonably close agreement between simulated and observed days to anthesis of Kanchan and Sowgat, but maturity dates were generally overestimated by 3-6 days. Hundal and Kaur (1997) validated CERES Wheat for various sowing dates and years from 1985-86 to 1992-93 in Ludhiana, northwest India. The simulated number of days to anthesis of HD-2329 was within –9 to +6 days and that of maturity was within –6 to +3 days of observations. The largest underestimates of both anthesis and maturity dates were for the earlier-sown crops (early November) in some years. Some discrepancies were also observed for various sowing dates across years but the deviations were inconsistent. Timsina et al. (1995) compared the performance of CERES Wheat, Wheat_W (based on SUCROS 2; van Laar et al., 1992) and WATBAL (Wopereis, 1993), at Pantnagar, a sub-tropical environment in India and at Los Banos, a tropical environment in the Philippines. CERES Wheat overestimated the number of days to anthesis of RR21 and HD2009 by 4 to 10 days in 9 out of 11 treatments while it overestimated the number of days to maturity by 5 to 27 days for 4 treatments and underestimated it by 4 to 10 days for 4 treatments. In a temperate climate, Seino (1995) reported that the model predicted the number of days from sowing to physiological maturity very closely in northern and central Japan (within 1%) of observed days and slightly underestimated it (within 2.5% of observed days).

Testing against the data reported here suggests that CERES Wheat performed fairly satisfactory in Bangladesh, India and Japan (RMSE=4.5 and 5.1 d and SE=3.8 and 4.8 d, respectively, for anthesis and maturity), however further evaluation is required for the range of rice-wheat environments in Asia and Australia.

5.2. Growth and grain yield

Results from IRRI, Los Banos, with ANZA, UPLW1, and UPLW3 showed that CERES Wheat and Wheat_W did not perform satisfactorily in a tropical environment, but it was suggested that with further refinements they could be used with greater confidence (Timsina et al., 1995).

Hundal and Kaur (1997) found generally close agreement between observed and simulated (CERES Wheat v.2.1) yield and yield components of wheat cv. HD-2329 over eight years (1985-86 to 1992-93) in the sub-tropical envirnoment of Ludhiana, northwest India. Simulated grain weights were within 88 to 113% of measured weights, grain yields within 80 to 115% of measured yields, and biomass yields within 93 to 128% of measured yields. They concluded that the model can be used for prediction of wheat yield for the central irrigated plains of the Indian Punjab, but that there is also a need for a closer examination of the quantitative relationships governing the partitioning of photosynthates into biomass and grain yield. At Pantnagar, northwest India, the simulated yields of RR21 and HD2009 were within 5% of the observed yields for 8 out of 13 treatments. In northern Bangladesh, CERES Wheat simulated grain yield quite satisfactorily for eight treatment combinations of N, water, and sowing dates (Timsina et al., 1998). Heng et al. (2000) also reported good agreement between observed and simulated grain and biomass yields in many locations across the world including India, Bangladesh and China. Nain et al. (2002) used combined analyses from the technology-trend model and CERES Wheat for several locations in India (Amritsar, Faridabad, Jaipur, Bhopal, Lucknow, Patna). Using the coefficients of HD2329 derived by Hundal and Kaur (1997) they found an overall RMSE of 0.16 t/ha (5.6%) against a mean grain yield of 2.82 t/ha.

In temperate environments, Seino (1995) found that CERES Wheat predicted grain yield of wheat within 2% of observed values in northern and central Japan, and within 1% in southwest Japan. O'Leary (2000) compared the accuracy of eight simulation models, including CERES Wheat, for several low yield potential temperate environments, including Australia. He concluded that underestimation of wheat yield under stressed conditions was a common problem of all models, and suggested that new models may need to be derived for accurate simulation, especially at very low yield levels (< 1 t/ha).

Otter-Nacke et al. (1986) validated an early version of CERES Wheat for a range of cultivars grown across world, including rainfed environments across Australia - Rutherglen (Victoria), Wagga Wagga (NSW), Murrumbateman (NSW), Wogan Hills and Lancelin (Western Australia), and the Waite Institute, Adelaide (South Australia). At Wogan Hills, Adelaide, and Wagga Wagga, the model was tested for its sensitivity to N rate and splits and was compared against observations from a range of experiments. For zero-N rates at all sites the model either over or underestimated grain yield. At Wagga Wagga, the simulated grain yield and shoot N uptake was not sensitive to N rates ranging from 0 to 240 kg/ha, but at the other two sites it was sensitive for rates ranging from 0 to 160 kg/ha. For two experiments at Wagga Wagga, there was good agreement between simulated and observed yields, but for the rest of the experiments at that site, the model slightly overestimated the yields at high N rates. There was a close match between simulated and observed N uptake, and the model simulated seasonal LAI and above ground biomass fairly satisfactorily in one year (1981) but overestimated both LAI and biomass in another year (1980. At Rutherglen, there were large discrepancies between measured and predicted values for a range of parameters, with the model underestimating LAI and stem weight over time, but overestimating tiller density. At Murrumbateman, the model simulated the above ground dry matter and LAI over time fairly well, and tiller density marginally well, but grossly overestimated root weight. At Wogan Hills and Adelaide the model simulations were sensitive to N rate but the model grossly overestimated the shoot N uptake. At Lancelin, where 77 kg N/ha was applied in various splits (0 to 5), the model was highly sensitive to N splits, and in 60% of treatments there was a good agreement between simulated and observed yields.

Smith et al. (2003) compared yields of Janz, Yecora, and Bindwarra simulated by CERES Wheat and SWAGMAN® Destiny for several field and lysimeter experiments in the rice-growing region of southern Australia. Both models predicted yields very accurately in all cases except for Destiny in one case Both models accurately simulated root length density and volumetric moisture content at a range of depths, the time course production of above ground biomass and LAI, and daily evapotranspiration.

CERES Wheat has also been evaluated in many other countries across the world. For example, Otter-Nacke et al. (1986) compared predicted and observed wheat yields from 283 experiments from many temperate environments in the USA, Europe, south Africa and Australia. The model was able to explain about 60% of the variation in grain yield. Other examples of CERES Wheat evaluations and applications involved several sites across the world (Jones et al., 2003), including sites in Canada (Fei and Ripley, 1988; Moulin and Beckie, 1993; Toure et al., 1994; Beckie et al., 1995; Tubiello et al., 1995; Chipanshi et al., 1997, 1999), USA (Mearns et al., 1992; Rosenzweig and Tubiello, 1996; Southworth et al., 2002), Europe (Kovacs and Nemeth, 1995; Bacsi and Zemankovics, 1995; Castrignano et al., 1997; Landau et al., 1998; Saarikko, 2000; Gabrielle et al., 2002), South America (Baethgen and Magrin, 1995; Travasso and Delecolle, 1995; Savin et al., 1995; Messina et al., 1999), New Zealand (Porter et al., 1993).In most cases CERES Wheat performed satisfactorily except in the studies of Porter et al. (1993) and Landau et al. (1998). Porter et al. (1993) tested three wheat models (AFRCWHEAT2, CERES Wheat, SWHEAT) against data from five well-irrigated and well-fertilized experiments in Lincoln, New Zealand, and reported that CERES Wheat was intermediate in performance in predicting the number of days to anthesis, and grossly overestimated the proportion of PAR intercepted before anthesis, but predicted the final grain yield accurately. They concluded that CERES Wheat requires improvement in predicting development and in estimating PAR interception. Landau et al. (1998) compared the performance of three wheat models (CERES Wheat v.3.0, AFRCWHEAT2, and SIRIUS) against observations from 341 well-managed and well-fertilized winter wheat trials across UK, and concluded that none of the models was able to predict historical grain yields between 1976 and 1993 and with substantial inaccuracy in model predictions of both yield and yield loss due to water limitation. CERES Wheat generally underpredicted yield and had the largest root mean square error (RMSE) of 3.0 t/ha reflecting large inaccuracy given the range of observed yields of 5 to 13 t/ha. Landau et al. (1998) concluded that more work is needed before yield predictions can be used with confidence in decision support or climate change assessment in the UK.

Hasegawa et al. (1999) tested the soil N transformation, water balance, and temperature sub models of CERES Wheat and Maize to assess N release from a legume cover crop (LCC) and maize residue during a fallow period at Davis, California. The model overestimated soil temperature by 1-3^{o}C for early LCC incorporation and over- or underestimated soil temperature by 1-3^{o}C for late LCC incorporation, but with some exceptions, soil water content was simulated well. The observed and simulated total inorganic soil N to a depth of 80 cm differed by 20%. Although soil temperature, water content, and N release from the legume cover crop were reasonably well simulated, the nitrification capacity factor, decrease in inorganic soil N after incorporation of the maize residue, and flushes of mineralisation releasing inorganic N after rainfall or irrigation were not predicted accurately, indicating that the immobilization and /or denitrification subroutines should be revisited. Hasegawa et al. (2000) also evaluated the ability of CERES Wheat to predict N dynamics during wheat and maize crops following legume cover crop incorporation. The observed soil inorganic N content and crop N uptake were mostly within 20% of predicted values, but soil temperature was overpredicted by about 10^{0}C. They concluded that the CERES models could give a rough estimate of the N budget in a wheat rotation following a fallow or late incorporated legume cover crop, and that further improvement would be required to accurately predict legume cover crop decomposition, inorganic N release and soil temperature.

These findings suggest that the performance of CERES wheat is variable. In the few evaluations in the rice-wheat areas of Asia and Australia, the model performed fairly satisfactorily for grain yields but less satisfactorily for biomass, with RMSE of 0.5 and SE of 0.49 t/ha for grain yield, and RMSE of 1.82 and SE=1.47 t/ha for total biomass. CERES Wheat requires further evaluation in these environments, including over a range of water and N conditions. The response to high temperature during grain filling also needs further consideration, as this can be a major limit to yield in many rice-wheat locations.

5.3. Conclusions on the evaluation of CERES Wheat

CERES Wheat has been evaluated in a wide range of environments across the world, including rice-wheat growing areas in sub-tropical Asia and temperate Australia. While performance of the model has often been good, there have also been some alarming examples of inadequate performance in high and low yielding environments.

The limited evaluation in Asia suggests that CERES Wheat was generally satisfactory in predicting key development stages and grain yield. As for CERES Rice, the CERES Wheat also needs to be evaluated for a wider range of parameters across a range of hydrological and fertility conditions in the rice-wheat areas of Asia and Australia.

6. Evaluation of the CERES Rice-Wheat sequence model

Only one study (Timsina et al., 1996) reports validation of the CERES Rice-Wheat sequence model. In that study, rice and wheat crops grown in sequence for 20 years at Pantnagar, India, were used to validate the rice-wheat sequence model using the sequential mode of the DSSAT. Planting dates, cultivars, and initial conditions varied across years. The model was reset each season using observed initial soil mineral N and soil moisture content, and actual sowing dates and cultivars. The model satisfactorily predicted the fluctuations in yield of rice and wheat and the long-term yield trend over 20 years. With 120 kg N/ha fertilizer for each crop, simulated yields were close to the experimental yields in 33 out of 40 crops. With no N fertilizer, simulated yields of both rice and wheat were generally underestimated. The discrepancies between observed and simulated yields were considered to be due to insufficient soil model input data, especially soil N and organic C prior to each crop.

Timsina et al. (1995) also tested the sensitivity of the CERES Rice and Wheat for a range of variables (moisture regimes, planting dates, weather years, and N application rates) that influence the productivity and sustainability of rice-wheat systems in the rainfed and irrigated ecosystems on a fertile and an infertile soil in a sub-tropical environment at Pantnagar, India. In the infertile soil, the simulated rice yields increased with increasing level of fertilizer N while in the fertile soil, yields levelled off for application rates higher than 90 kg N/ha. These results suggest that both models were sensitive to a number of management related variables and that they could be used to study the sustainability related issues in rice-wheat systems.

7. Calibration and evaluation of SWAGMAN® Destiny models

Calibration and validation of SWAGMAN® Destiny has been limited to Australia, except for validation against observations for pre-kharif mungbean in Bangladesh, using the data of Hossain et al**.** (1990). The model performed fairly satisfactorily over the two years of available data (Timsina et al., 2000).

In Australia, 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 agreements for 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 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.

SWAGMAN® Destiny showed a good agreement between simulated and the observed wheat growth over the growing season at one experiment at Coleambally and also reasonable to good agreements between simulated and observed yields, soil water contents at different depths, depth to the watertable, evapotranspiration, and root length density (Smith and Humphreys, 2001). More recently, SWAGMAN® Destiny was evaluated against the performance of wheat growing in lysimeters and fields in the rice growing areas of south eastern Australia (Smith et al. 2003; Xevi et al., 2003). The model was calibrated for three wheat varieties – Bindawarra, Janz and Yecora, and validated for a range of crop parameters and soil water content and depth to the watertable using independent data sets. Agreement between predicted and observed values for all parameters was good, except for yield in one situation due to a rise in the regional watertable. Consistent with this, the model simulated the soil profile a lot drier than it really was, which resulted in a lower yield prediction.

8. Applications of CERES Rice and CERES Wheat

Mathews and Stephens (2002) categorized the main applications or needs of models into 3 categories: as tools in research, in decision support, and in education and training. Examples of research applications included identification of desired crop genotype characteristics, investigation of management options, cropping or farming system analysis, investigations of impact of climate change on crop productivity, and prediction of greenhouse gas production. Models can be used to assist both tactical decision making (such as irrigation scheduling, and fertiliser and pest management), or in strategic decision making, such as planning for climate change or to avoid salinisation, yield forecasting and planning for national food requirements. Models can also be useful in teaching crop and soil processes and crop system behaviour in response to weather, management and site conditions.

The applications of CERES Rice and Wheat identified identified in this review are summarised in Table 9, under seven categories: yield forecasting, yield trends and gap analyses, crop management, extrapolation to other locations, climate change, greenhouse gas emissions, pest and disease management, and policy.

8.1. Yield forecasting

CERES Wheat has been used in yield forecasting studies in Australia. For example, Stephens et al. (1989) reported that CERES Wheat was adapted by the Western Australian Department of Agriculture's Merredin Research Station in the eastern wheat belt of Western Australia as early as 1983. During that time, the validated model was primarily used to estimate the stored soil moisture at sowing. From this information plus the expected seasonal rainfall, the model was used to predict wheat yield (McMahon, 1983). Stephens et al. (1989) developed a simple model based on CERES Wheat for relating water stress to yield and for forecasting yield for the Merredin district of Western Australia. However, there are no reports of use of CERES Rice in yield forecasting studies in both Australia and Asia and of CERES Wheat in Asia.

8.2. Yield gap analyses

An important role for crop models is the estimation of yield potential and yield gaps at site, regional and national levels, identification of reasons for the gaps, and evaluation of management options for closing those gaps. CERES Rice and Wheat have been used for determining potential yields and for identifying yield gaps in rice and wheat in many locations of many countries. The results generally reveal large gaps between potential yields and farmer yields.

Jintrawat (1995) compared long-term yields with simulated yields using CERES Rice for provinces in north and northeast Thailand. Simulated yields were higher than provincial yields by 0.4 (north) and 1 t/ha (north east) due to losses caused by insects, diseases, rodents, and lodging. Jintrawat (1995) estimated long-term potential yields for northern Thailand (Chiang Mai) (4 to 4.5 t/ha) and northeast Thailand (Khon Kaen) (2 to 3.5 t/ha). Boonjung (2000) also estimated potential yields of rice in Thailand, finding lower potential yields in the northeast (2 t/ha) than in the southwest (3.2 t/ha), and with greater yield variability in the northeast.

In West Java, farmers' yields ranged from 4.0 to 4.1 t/ha while simulated yields ranged from 4.4 to 4.7 t/ha, suggesting a small yield gap in this part of Indonesia. Pinnschmidt et al. (1997) estimated weather-limited and weather plus N-limited yields using CERES Rice v.2.1. The difference between observed and weather-limited simulated yields averaged about 35% in the Philippines, 45% in Vietnam, and 55% in Thailand. The gaps were mainly due to N limitation in Thailand, where soil N and fertilizer use are low. In the other two countries the gaps were mainly due to other constraints including low soil organic carbon, water deficit, and disease and pest damage, and partly due to low N. Timsina et al. (1997) predicted the potential yields of rice, wheat and maize for various planting dates and sites in the hills and plains of Nepal. Potential yields of rice cv. Masuli from 1983 to 1986 varied from 7.1 to 8.0 t/ha at two sites, while Chaite 2 varied from 8.3 to 10.0 t/ha. District average yields of rainfed Masuli without any added N ranged from 1.3 to 3.6 while yields under partial irrigation and with 100 kg N/ha varied from 3.5 to 5.0 t/ha. Yields of Chaite 2 were higher than yields of Masuli under both partial irrigation and rainfed conditions at both sites. Using CERES Rice v.3.0, Saseendran et al. (1998b), reported average potential yield across 4 transplanting dates of 15.4 t/ha for cv. Jaya in Kerala, India, compared with average actual yields of 5.2 t/ha under rainfed and sub-optimal N management practices. The very large yield gaps in Kerala suggested the need for capturing and storing the surplus rainwater during the rainy season for irrigating crops during the non-rainy periods.

Using CERES Wheat v.3, Timsina et al. (1997) reported potential yields of RR21 from 2.3 to 8.4 t/ha and of UP262 from 3.6 to 8.9 t/ha for four sites in Nepal. Water and N limited yields (rainfed and no added N) varied from 0.8 to 3.4 while rainfed yields with 80 kg N/ha varied from 1.6 to 4.3 t/ha. District average yields were similar to water and N limited yields. Sherchand (1998) estimated potential yield of RR21 for three dates of sowing at three sites in Nepal (Chitte and Khumaltar in the mid-hills and Bhairahawa on the plain). Potential yield of wheat in 1997, estimated using CERES Wheat v.3, varied across sites and was highest for 2 December sowing at Khumaltar (~5.6 t/ha) and Bhairahawa (~4.7 t/ha), while at the third site, it was highest for 12 November sowing (~5.2 t/ha). Both of these studies indicated large gaps between farmers' yields and potential yields.

Timsina et al. (1997) estimated long-term (1979 to 1992) rice-wheat system potential yields, and yields at 120 kg N/ha (recommended N) and zero N using rice cvs Jaya and Pant-4 and wheat cvs RR21 and UP262 at Pantnagar. Potential yields of the rice cultivars for 1979 to 1992 with 150 kg N/ha, varied from 4 to 8 t/ha, and were 0.5 to 2 t/ha higher than the yields at 120 kg N/ha. In wheat, however, long-term potential yields and yields at 120 kg N/ha were similar and varied from 4.5 to 5.7 t/ha. The study suggested considerable gaps between yield potential and yields being achieved by researchers for rice but not for wheat in rice-wheat systems of Pantnagar. Aggarwal et al. (2000a) 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 as stand alone models These potential yields are much higher than the national average rice-wheat system yields in long-term experiments (8.1 t/ha) or the Punjab average systems yield (7-8 t/ha).

8.3. Yield trend analysis

Yield stagnation or decline in rice and wheat grown separately or in sequence is a concern for food security in south Asia. Aggarwal et al. (2000a) used ORYZA1N and CERES Rice to predict yield trends of rice and CERES Wheat and WTGROWS for wheat for several districts in northeast India. Measured district rice yields declined in many districts (Karnal, Gurdaspur, Kapurthala, Ludhiana, and Sangrur) but increased in others (Kurukshetra and Amritsar). Wheat yields increased over time in all districts, but at a slower rate in recent years compared with the previous decade. The decline in rice yields observed in a long-term experiment in Ludhiana was also predicted by CERES Rice, but not by ORYZA1N. For wheat, however, both models predicted yield trends consistent with the observed trends. Pathak et al. (2003) also compared measured district rice and wheat yields with potential yields predicted using CERES Rice and CERES Wheat for several districts (Ludhiana, Karnal, Delhi, Kanpur, Varanasi, Faizabad, 24-Pargana, Raipur, Pantnagar) in India. The district average yields of rice varied from 2.1 t/ha at Raipur to 5.6 t/ha at Ludhiana, and yields of wheat varied from 1.0 t/ha at Raipur to 4.3 t/ha at Ludhiana. Long-term (1985-1989) potential rice yields ranged from 7.7 t/ha at Raipur to 10.7 t/ha at Ludhiana, while potential wheat yields ranged from 5.2 t/ha at 24-Pargana to 7.9 t/ha at Ludhiana. The average annual change in potential yield of rice ranged from –0.12 t/ha/yr in Delhi to 0.05 t/ha/yr in Kanpur, with significant trends for yield decline in 4 out of 9 districts. The rate of annual wheat yield change ranged from –0.07 t/ha/yr in Delhi to 0.04 t/ha/yr at Faizabad and Pantnagar, none of the yield changes being significant.

Models suitable for examining long-term yield trends require the capacity to address issues related to carryover of soil organic matter and nutrients between each phase of the cropping system. Timsina et al. (1996) used the CERES Rice and Wheat models embedded within DSSAT v.3.0 to explain the yield trends in rice and wheat in a long-term rice-wheat experiment at Pantnagar, India. There was a clear trend of decreasing rice yields over 20 years, especially since year 11, and the decline was greatest for the control (zero N) and least for the 120 kg N/ha treatment. Wheat yields, on the other hand, consistently increased over time, with the greatest increase with 120 kg N/ha and least for zero N (Timsina et al., 1995, 1996). Linear regressions of year against simulated yield suggested that rice yield declined and wheat yield increased. The reasons for the predicted yield trends are not known. Regressions of year number against simulated soil organic N and C for 120 kg N/ha showed a steep decline in soil organic C and N over time (Timsina et al., 1996). This suggested that the decline in rice yields was due to declining soil organic C and N, however the steep decline was not realistic. DSSAT v.4.0 with the improved soil organic matter routines based on CENTURY version may simulate the SOM dynamics more realistically and needs to be tested.

8.4. Devising agronomic management strategies

CERES models have been used in devising tactical management strategies such as optimum sowing dates of wheat, transplanting dates of rice, plant population for rice, and N management strategies in rice and wheat in several Asian countries.

Singh and Thornton (1992) used CERES Rice to evaluate the effect of urea application method on N loss and efficiency for dry season rice at Pila, Philippines. They compared broadcasting into 5 cm of floodwater, moderate incorporation in the soil without floodwater with a mixing efficiency of 30%, and deep-point placement without floodwater with a mixing efficiency of 95%. The floodwater in the two latter cases was raised to 5 cm depth shortly after fertilizer application. The model predicted rapid and interactive transformations in the floodwater within two days of fertilizer application in the broadcast and moderately incorporated treatments, and little fertilizer N reaction in the floodwater in the deep-placed urea treatment. The biological (algal) activity and biological transformations leading to higher floodwater pH were rapid in the broadcast treatment, consequently ammonia volatilization was also higher. Nitrogen losses declined with increasing degree of incorporation and were negligible when urea was deep-point placed. Buresh et al. (1991) also used CERES Rice to assess year-to-year variability in response to N application for two transplanting dates (15 January and 15 July) in Philippines. The model consistently predicted higher N response with the January than July transplanting and greater NH_3 loss for July than January transplanting. At Pantnagar, India, CERES Wheat predicted a small response to applied N in fertile soil but a large response in infertile soil (Timsina et al., 1995).

Optimum sowing and transplanting dates have been investigated for wheat and rice at a range of locations using the CERES models. At Pantnagar, simulated rice yields were highest for early transplanting (13 June to 13 July) and lowest for late transplanting (27 August). Simulated wheat yields were also highest for early planting (17 October to 16 November) and least for late plantings (1 December to 30 January) (Timsina et al., 1995). Timsina et al. (1997) also used CERES models to identify the optimum planting dates for a range of cultivars of rice and wheat for several locations in Nepal. For rice, the optimum transplanting date was 15 May while for wheat the optimum sowing date was 15 November for most locations. In Nashipur, Bangladesh, the optimum sowing for wheat as simulated by CERES Wheat was 15 November (Timsina et al., 2001). Saseendran et al. (1998a,b) also identified the optimum transplanting dates for rice (cv.s Jaya and IR8) under rainfed conditions for five sites in Kerala, India. If only one crop were to be grown per year, the optimum transplanting dates would be later (4^{th} week of June at one site and 1^{st} week of July for four sites), but if two crops were grown, the dates would be earlier (1^{st} to 4^{th} week of June for all sites).

Hundal and Kaur (1999) evaluated the age of seedlings at transplanting, number of seedlings per hill, number of hills/m^2, and date of transplanting for rice in the Indian Punjab. CERES Rice predicted that the optimum date of rice transplanting was 15 June, but that earlier-transplanted (1 June) rice would perform better if seedling age were reduced from 40 to 30 days. Increasing plant population from 11 to 44 hills/m^2 decreased yields while increasing the number of seedlings per hill from 1 to 6 increased yield. Young seedlings (20 to 30 d old) gave better yields than old seedlings (40 d old). Boonjung (2000) identified the optimum transplanting date of rice cv. KDML 105 (photosensitive) to be 1 to 15 June in Nakhon Ratchasima province in northeast Thailand.

Heng et al. (2000) also used CERES Wheat to simulate the effect of irrigation and fertilizer rates on nitrate leaching in Asia, Africa, and South America. Such simulation results could be useful for policy identifying management to minimise pollution of groundwaters by leaching.

Jintrawat (1995) applied CERES Rice to develop long-term strategies related to planting dates, planting methods (dry-seeded rice, DSR, or transplanted rice, TPR), organic residue rates, N rates, water regimes (rainfed or irrigated), and soil types using cumulative probability functions**.** Strategic analysis was done for various combinations of management practices using 10 to 50 years of historical weather data. The results revealed that the CERES Rice could be used to find alternative ways to improve rice production.

8.5. Extrapolation to other locations

Models can be used to extrapolate results to other sites and climates over space and/or time. These could include potential sites where a particular system has not been practised previously, and the impact of climate change predictions on crop performance (section 10.6).

Timsina et al. (1998) calibrated and validated the CERES Rice and Wheat models and established the long-term yield trends for rice-wheat systems at Nashipur in northern Bangladesh. Using the minimum soil, crop, and weather data, they then predicted the long-term yield trends of two rice (BR14 and BR11) and two wheat (Kanchan and Sowgat) cultivars for low (zero N, rainfed) and high (120 kg N/ha, irrigated) input systems for three sites in north (Dinajpur District), northwest (Jessore District) and central (Gazipur District) Bangladesh. Across sites, years, moisture and N regimes, BR11 rice always outyielded BR14, consistent with experimental results. Wheat yields across sites and years were highest at Nashipur due to lower minimum temperatures and higher solar radiation during the growing season. Conversely, yields were lowest at Gazipur due to higher temperatures and lower solar radiation. The results also indicated that without added N fertilizer, N will be limiting for both rainfed and irrigated rice-wheat systems in Bangladesh.

8.6. Impacts of climate change on yields

Both CERES Rice and CERES Wheat have been used to study the effect of global climate change on rice and wheat production in Asia. Climate change scenarios were generated either by changing the values of weather parameters (temperature, radiation, rainfall) and CO_2 concentration singly or in combination, or by General Circulation Models (GCMs) of which four were most commonly used **-** the Goddard Institute for Space Studies (GISS) model (Hansen et al., 1983), the Geophysical Fluid Dynamics Laboratory (GFDL) model (Manabe and Wetherald, 1987), the United Kingdom Meterological Office (UKMO) model (Mitchell et al., 1989), and the Canadian Climate Centre (CCC) model (Wilson and Mitchell, 1987). The difference between $1\times CO_2$ and $2\times CO_2$ mean monthly GCM temperatures and the ratio of $2\times CO_2:1\times CO_2$ monthly GCM precipitation totals were determined using the GCMs, where $1\times CO_2$ refers to current climate conditions, and $2\times CO_2$ refers to the climate that would occur with a doubling of the CO_2 level. The daily weather data for for use in the crop models under climate change were adjusted based on the changes in the monthly means generated by the GCMs.

Bachelet et al. (1993) and Bachelet and Gray (1993) reviewed the three rice models (MACROS, CERES Rice, and RICESYS) to evaluate their suitability to assess the impact of global climate change for rice-growing areas in Asia. Grain yield response of both MACROS and CERES to temperature and CO_2, and of RICESYS to temperature, agreed well with the glasshouse experimental data. MACROS simulated a sharper decrease in potential yield than CERES, agreeing with experimental data of Baker et al. (1990a,b), but CERES predicted a lower impact of temperature change on potential rice yield than MACROS (18% and 62% yield decrease for an increase in temperature from 25^0C to 30^0C, respectively), consistent with the results of Baker et al. (1990b). CERES Rice predicted a 15% increase in potential yield due to doubling of CO_2 concentration compared with a 9% using MACROS, both results well below the 47% increase observed by Baker et al. (1990b).

In the Philippines, Singh and Ritchie (1993) studied the impact of climate change on crop growth and yield of IR58, a heat-sensitive cultivar, and an imaginary heat-tolerant cultivar, and the nutrient dynamics at IRRI, Los Banos, and at Munoz, Nueva Ecija. As temperature was increased by 0 to 5.5 ^{0}C, growth duration was reduced by up to 10 d, reducing the potential yield of both cultivars. The reduction was, however, less for the heat-tolerant cultivar. The simulated grain yields over the entire temperature range were markedly higher with a CO_2 concentration of 540 ppm, and with the exception of the zero N treatment, grain yield of the heat-tolerant cultivar was always higher with enriched CO_2 concentration. Water-use efficiency was lower with increased temperature and no N input, and for the heat-sensitive cultivar. Increased temperature also increased mineralization rate from 0.29 to 0.33 kg N/ha/d for zero N and from 0.35 to 0.42 kg N/ha/d with 120 kg N/ha. The results suggested that in unfertilized conditions, management factors improving soil N availability would increase grain yield because as much as 60% of the plant N would be contributed by mineralization. Escano and Buendia (1994) also studied the impact of climate change on rice yields in Batac and Los Banos in the Philippines. Projected climate change caused simulated rice yields to decrease at both locations, but the decreases were larger at Los Banos, which has a lower latitude. The effects of increased temperatures and increased CO_2 concentration were similar to those reported by Singh and Ritchie (1993). Possible adaptation strategies included earlier planting and changing cultivars, which could, however, bring major changes to the current farming systems in the Philippines.

Singh and Padilla (1995) studied the effect of climate change on rice yield and adaptive management practices in the Philippines in more detail. They reported that, under the current temperature regime, there would be beneficial effects of CO_2 enrichment from current (330 μmol mol^{-1}) to high (660 μmol mol^{-1}) concentrations in terms of increased grain yield, reduced transpiration, increased water-use efficiency, increased radiation use efficiency, reduced N losses, and higher N-use efficiency. The trends would be reversed for all the above parameters for each ^{0}C increase in temperature from 0 to 5^0C at each CO_2 level. The increase in grain yield with high N at 660 μmol mol^{-1} concentration was much greater than at 330 μmol mol^{-1} concentration. At zero N, crop response to temperature was similar, but response to an increase in CO_2 concentration was very low, suggesting that the benefits of higher concentration would be more pronounced in high input irrigated rice. Further, some of the negative effects of temperature increase in warmer regions could be offset by the use of rice cultivars tolerant to high temperature-induced spikelet sterility, and by planting cultivars with longer growth duration, particularly longer grain-filling duration.

In the Philippines, Buan et al. (1996) also used CERES Rice v.3.0 in combination with results from four GCMs (CCCM, GFDL, UKMO, GISS) to assess the impact of climate change on two rice (IR64 and IR72) cultivars. The first three scenarios generally increased yields, but the GISS scenario decreased yields. Decreased rice yields were partly due to a decrease in the grain-filling period as a result of increased CO_2 concentrations resulting from increased day and night temperatures, but was also partly due to increased flooding that would be brought about by a 10% increase in rainfall. CERES Rice was unable to simulate the effects of strong winds that would result from typhoons.

Tongyai (1994) studied the impact of climate change on simulated rice production for four locations (Chiang Mai, Phitsanulok, Nankhon Sawan, and Bangkok) in Thailand using CERES Rice. Projected climate change caused yields (both upland and paddy rice) to decrease dramatically due to temperature increases. Yield decreases were partially counteracted by the physiological effects of increased CO_2. Despite differences among the GCM scenarios, locations and agricultural practices, rice yields under all climate change scenarios dramatically decreased in comparison with base-line yields.

In Indonesia, Amien et al. (1996) also used three models (GISS, GFDL, and UKMO) and generated several scenarios for Ngawi (East Java) and Sukamandi (West Java). The models predicted that doubling greenhouse gases would increase solar radiation by 1.2 to 2.1%, minimum and maximum temperatures by 7.6 to 16.8%, and rainfall by 20.5 to 91.7%. CERES Rice predicted that climate change could reduce rice yield by about 1% annually in East Java and slightly less in West Java.

Zhiqing et al. (1994, 1995) studied the effect of climate change on rice production in nine provinces in eastern, central-western and southern China. The studies compared baseline and doubled-CO_2 climate change scenarios generated by GISS, GFDL and UKMO. They also considered the physiological effects of CO_2 on rice growth for each scenario and examined several strategies for adapting to climate change. In both studies, simulated rainfed rice yields in all provinces decreased due to shortened growth duration as a result of increases in temperature and, at some provinces, due to sharp decreases in rainfall. Irrigation improved rice yield, especially in regions where rainfall decreased due to climate change. In rainfed rice, the direct effects of increased CO_2 concentration compensated for the negative effects of climate change in most sites, except where rainfall sharply decreased. In irrigated rice, rice yields increased in comparison with the baseline yields in the northern sites but decreased in the central and southern sites for all three GCM scenarios, suggesting that there is less compensation by the physiological effects of CO_2 in areas with high temperature. Under all climate change scenarios, the amount of water needed for irrigation increased greatly in areas where the rainfall decreased sharply, and ET of rainfed rice was usually less than that for irrigated rice, suggesting that rainfed upland rice could be developed in areas where irrigation water was not available. Further, an increase in temperature would increase the area for rice cultivation as the northern limits for double rice and triple rice could be moved northward by about 5-10^0 of latitude. As a result the cropping index would increase and the cultivar and management (planting date, etc.) conditions would have to be adjusted to the new conditions.

Saseendran et al. (2000) analysed the effect of climate change on rice productivity at five sites in Kerala, India. Changes in temperature ranged from –5^0C to +5^0C with an increment of 1^0C over the observed baseline climate data. Changes in rainfall ranged from –16 mm/d to 16 mm/d with an increment of 2 mm/d added to each rainy day. CO_2 levels ranged from 180 ppm to 1230 ppm. Across Kerala, an increase in CO_2 concentration led to a yield increase and enhanced water-use efficiency. Yield declined by about 6% for every degree increment in temperature up to 5^0C. The physiological effect of ambient CO_2 at 425 ppm compensated for the yield losses due to increase in temperature of up to 2^0C. There was a near exponential increase in rice yield for an increase in rainfall above observed values, but there was yield loss of about 8% for a decrease in rainfall by 2 mm/d. Aggarwal and Mall (2002) also predicted the impact of climate change under various scenarios (no change in weather, gradual change in CO_2 from 350 to 750 ppm in steps of 50 ppm, and temperature from 0 to 5^0C in steps of 1^0C, and interaction effects of different levels of CO_2 and temperature) on rice yield in Delhi, Patna, Puna, and Coimbatore. Rice yields increased by 1.0 to 16.8% in optimistic scenarios (low increase in temperature and high increase in CO_2) and decreased by 3.5 to 33.8% in pessimistic scenarios (low increase in CO_2 and high increase in temperature). Aggarwal and Mall (2002) considered that the magnitude of this impact could be biased by up to 32% depending on uncertainty in the climate change scenario, the level of management and the crop model used.

Karim et al. (1994) studied the impact of climate change on rice production at two contrasting locations (Mymensingh and Barisal) in Bangladesh. At both sites, simulated rice yield decreased significantly with temperature increases but this was offset by the physiological effects of CO_2. The study concluded that if CO_2 concentrations did not increase, or if the fertilisation effects of CO_2 were less than predicted, then rice production in Bangladesh could be negatively affected and the country's food security for the increasing population would be threatened from climate change.

Luo et al. (1995) used a combination model (CERES Rice coupled with BLASTSIM) in conjunction with weather generators from DSSAT to study the effects of global climate change on rice leaf blast epidemics for 53 locations in Philippines, Thailand, China, Japan, and Korea. The simulation allowed for analysis of distribution of the disease and estimated yield losses over a 30-yr period. The simulated climate change, i.e. temperature changes, had a significant effect on disease development, although this varied according to the agroecological zone. In cool subtropical or temperate zones such as in Japan and northern China, elevation of ambient temperatures resulted in higher risk of blast epidemics, whereas in warm humid tropics, lower temperatures resulted in reduced risk of blast epidemics. The yield loss caused by enhanced ultraviolet-B (UV-B) was normally around 9-10% and was independent of temperature change, and the deviation was much smaller than that caused by blast. Enhanced UV-B would cause much more severe blast when temperature changes to cooler than normal, especially in tropical countries.

CERES Wheat has been used to study the impacts of climate change on wheat production in Asia. Qureshi and Iglesias (1994) studied the impact of climate change on wheat at four sites (Jhelum, Khanpur, Gilgit, and D.I. Khan) in Pakistan. Wheat yield decreased dramatically under both dryland and irrigated conditions, due to a shorter season caused by temperature increase. The yield decreases were partly counteracted by the physiological effects of increased CO_2. The study concluded that Pakistan may be one of the regions more severely affected by climate change and that national wheat production may decrease substantially if climate changed according to GCM predictions. The adaptation strategies tested in Jhelum under the UKMO scenario did not compensate fully for the yield reductions, but changing cultivars combined with later planting decreased yield losses under irrigated conditions Rao and Sinha (1994) studied the impact of climate change on wheat production in Delhi and Hyderabad, two contrasting locations, in India. In all climate change simulations, wheat yields were lower than with the current climate, even with increased CO_2. Yield reductions were primarily due to a shortening of the wheat-growing season due to higher temperatures. Increased use of N fertilizer and plant population slightly reduced the negative impacts of climate change on yield.

Many studies used two or three CERES models to study the effect of climate change on a range of crops. For example, Seino (1994,1995) determined the impacts of climate change for various scenarios (GISS, GFDL, and UKMO) for rice, wheat, and maize in several locations in northern, central, and southwestern Japan. In southwestern Japan wheat is grown in rice fields in winter. Increasing temperature by 2 and 4 ^{0}C reduced the growth duration of rice by 9 to 32 d and reduced yield by 9 to 22%. Decreased precipitation did not have any adverse effect on rice yield as most rice is fully irrigated in Japan. Increasing CO_2 concentration to 555 ppm increased rice yield by up to 20%. Increasing temperature increased irrigation requirement, and increasing precipitation and CO_2 concentration reduced irrigation requirement. High temperatures shortened the growth duration of wheat by 8-30%, and decreased ET by 5-9% and yield by 17-30% in northern Japan. The effect of high temperatures was a little less in southwestern Japan, reducing growth duration by 10-20%, ET by 3-4%, and yield by 7-15%. Increasing precipitation and CO_2 concentration increased the grain yield of wheat. While increasing CO_2 compensated for the effect of increasing temperature in central and northern Japan, it didn’t compensate in southern Japan. Early planting, irrigation, and new cultivars adapted to climate change were considered to be possible adaptation strategies in both rice and wheat. In most cases in northern Japan, yields increased under climate change with earlier planting, however, in Kyushu in southern Japan, earlier planting did not improve yields due to high temperature stress, and new cultivars better adapted to the new climate would be required.

Hundal and Kaur (1996) used CERES models to study the effects of climate change on rice, wheat, maize and groundnut in Ludhiana, India. Scenarios included the effect of changes in each parameter separately and in combination, with daily increases in temperature (up to 3^{0}C above normal), solar radiation (up to 10%), precipitation (up to 50%) and CO_2 concentration (up to 600 ppm). Hundal et al. (1998) also studied the effect of climate change on the yields of rice cv. PR 106 under various scenarios, also in Ludhiana. Increased temperature advancee wheat maturity, but delayed rice, and reduced leaf area, biomass and yield more in wheat than in rice. A 10% decrease in radiation decreased the maximum LAI by 7.6% in wheat and 5.9% in rice, whilst a 10% increased LAI by 7.1 and 5.7%, respectively. Both biomass and grain yields of rice and wheat increased with increased solar radiation. iIncreasing CO_2 concentration to 600 ppm increased LAI, biomass, and grain yield of rice by 11, 7.7, and 8.7%, respectively. Decreased rainfall did not have any effect on rice and wheat yields as those crops were fully irrigated. The interaction between temperature and solar radiation didn't have any effect on phenology. Negative effects on LAI, growth and yield of wheat were further intensified where both temperature and radiation were increased. In rice, however, the adverse effect of an increase in temperature by 1 ^{0}C on growth and yield was compensated for by increasing radiation by 5%. Increasing both temperature and CO_2 concentration reduced the maximum LAI, biomass and grain yield of rice.

Timsina et al. (1997) analyzed the effect of climate change for 12 scenarios (effect of temperature, CO_2, and solar radiation separately, and in their various combinations) on grain yields and phenology of rice, wheat, and maize for several locations in the hills and terai of Nepal. There were significant effects of climate change on the yield and phenology of all crops. Temperature had the greatest effect. Increasing temperature shortened growth duration, decreasing grain and biomass yields, while decreasing temperature increased duration and grain yield. Increased solar radiation or CO_2 increased yield without affecting growth duration. The increased temperatures had less negative effect on rice than on the other two crops. As has been observed in many other studies, the positive effects of increased CO_2 were offset, to varying extents, by the negative effects of higher temperatures and increased rainfall There were interactions between weather variables for both rice and wheat, and the effects of climate change were different for different cultivars and sites. The main conclusion was that the major negative effect of climate change on yields in Nepal was due to temperature increases, not rainfall changes. In another study in the western districts of Nepal, wheat yield increased with increasing CO_2 and temperature (1-2 ^{0}C) in the hills but decreased on the plains (K. Sherchand, personal communication 2002). Thus climate change could have great implications for crop productivity and food security of Nepal.

Lal et al. (1998) predicted rice and wheat yields for various climate change scenarios (increase or decrease of maximum and minimum temperatures, CO_2 concentrations, and various water management levels) for Delhi, Hissar, and Ludhiana. Greater yields of both crops (15 and 28%, respectively) were predicted for doubling of CO_2 levels, but this was nearly cancelled out by 3^{0}C and 2^{0}C temperature rises during the wheat and rice seasons, respectively. While wheat yield was decreased by an increase in maximum temperature, rice was affected by an increase in minimum temperature. With increasing CO_2 and maximum and minimum temperatures, wheat yields would increase by 21% while rice yields would increase by 4%.

In Australia, Baer et al. (1994) used CERES Rice and Wheat with three climate change scenarios (GISS, GFDL, UKMO) to determined the potential impacts of climate change on rice and wheat production in Wongan Hills (western Australia), Roseworthy (south Australia), Horsham (Victoria), and Griffith and Narrabri (NSW). The scenarios included: (a) baseline climate, (b) GCM climate change scenarios alone, (c) GCM climate change scenarios with 555 ppm CO_2, (d) sensitivity analysis where base daily temperature and precipitation were modified by fixed amounts, and (e) changes in management to analyse adaptive strategies to climate changes (for example, planting dates and cultivars). In most sites, dryland wheat yields increased with rainfall increase, and both dryland and irrigated yields generally decreased with increasing temperature, the latter due to the shortening of the growing season. Rice yields also decreased slightly under various climate change scenarios. The most effective adaptative strategy to climate change was from changing the cold-resistant rice cv. Calrose to a more tropical cv. IR36. For wheat, by changing wheat sowing date from 30 May to 15 May to maximise water availability.

8.7. Prediction of greenhouse gas emissions

Mathews et al. (2000c) upscaled the local predictions by MERES to national levels to estimate the annual methane emissions from China, India, Indonesia, Philippines, and Thailand under various crop management scenarios involving organic amendments and duration of field drainage. Four scenarios were considered: (a) a 'baseline' scenario assuming no addition of organic amendments or field drainage during the growing season, (b) addition of 3 t DM/ha of green manure at the start of the season but no field drainage, (c) no organic amendments but drainage of the field for a 14-d period in the middle of the season, (d) addition of 3 t DM/ha of green manure and field drainage in the middle of the season. Adding 3 t/ha green manure at the start of the season increased emissions by 74 to 259% across the five countries as compared to the baseline scenario, while drainage during the middle of the season reduced emissions by 10 to 39%. The combination of organic amendments and field drainage increased emissions by 15-176%.

Grace (2002) used MERES to estimate methane production from water-seeded rice in two location (Griffith and Finley) of southeast Australia, and to identify potential strategies for reducing emissions. Emissions for 1989/1990 ranged from a low of 233 kg methane/ha on a Mundiwa clay loam with early midseason drainage and low residue retention, to a high of 1,112 kg methane/ha on a Beelbangera clay loam with continuous ponding and high amounts of residue retention. The latter value is a fourfold increase in the emissions that would be estimated for a 164-day crop using the current static National Greenhouse Gas Inventory approach for Australia. Emissions increased with stubble retention and decreased with midseason drainage, however yield was reduced with midseason drainage. Nitrogen fertiliser did not markedly affect the total methane flux. MERES slightly underestimated yields with high rates of N, which was attributed partly to limited data for determination of genetic coefficients.

MERES does not have the mathematical routines necessary to calculate N_2O losses. N_2O emissions should be taken into account in future studies as the global warming potential of this gas is over 15 times that of methane. N_2O emissions are likely to be more significant where rice is not continuously ponded..

8.8. Pest and disease management

Pinnschmidt et al. (1990) coupled simple pest population models to CERES Rice to investigate the effects of different stem borer control strategies on yield loss. Early control with an insecticide with an 80% ‘knock-down’ effect resulted in less yield loss than late control. Pinnschmidt et al. (1995) then developed an approach to link population models for leaf blast, panicle blast, sheath blight, leaf folder, stem borers, and plant hoppers to the CERES Rice model. Development of each disease or pest was modeled using a generic type model, derived from a paralogistic growth function. Pest effects were introduced into the crop simulator by mimicking effects at the physiological process level. The physiological processes and variables affected were: light-use efficiency, photosynthesis, partitioning, amount and translocation of carbohydrates, evapotranspiration, LAI, stand density, senescence rate, grain filling, and panicle weight. Pinnschmidt et al. (1990, 1995) were thus able to simulate the damage effects of single or multiple pests (defoliators, weed competition, leaf blast, and sheath blight) using CERES Rice in northwest Philippines, northwest Thailand, and south Vietnam.

8.9. Aiding government policy and strategic planning

CERES models have also been used to estimate national food production and thus aid government policy makers. For example, in 1991/92 there was an unexpected shortfall in the size of its winter wheat harvest in Albania and USAID wanted to determine to what extent wheat imports might be offset with emergency N fertilizer imports. CERES Wheat was then used to test the effect of a single N top-dressing applied at different times during the spring, the results of which the USAID was able to use to evaluate the potential benefit of imported N and the importance of timing applications. They decided that it was worth it, and it marked the beginning of a substantial aid package to Albania for improving fertilizer markets and availability in the country (Bowen and Papajorgji, 1992). Chou and Chen (1995) reported that combined use of satellite imagery, GIS and CERES Rice was useful for mapping potential land productivity and suitability under irrigation in Taiwan. In Java, Indonesia, there is a concern that rice self-sufficiency, maintained since 1984, could be threatened by climate change. Thus Amien et al. (1996) used three models, including CERES Rice, to simulate the effect of climate change to aid policy makers in planning for the effects of recurring droughts and other possible changes on national food production. The simulations suggested that climate change could reduce rice yields by an annual average of about 1% in East Java, and less in West Java, due to an increased incidence of drought.

Aggarwal et al. (2000b) also used several models, including CERES Rice and Maize, to determine potential crop yields with and without constraints including water, N, capital, labor, farmers’ income and options to maximize food production and farmers’ and regional incomes for the State of Haryana, India.

9. Applications of SWAGMAN® Destiny

SWAGMAN® Destiny was used in only one study in Asia, to evaluate options for increasing the yield of mungbean grown in the pre-monsoon season in Bangladesh (Timsina et al., 2000). Mungbean is a short duration crop which can be grown immediately prior to the main wet season rice crop in the eastern Indo-Gangetic Plain. 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. 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.

In rice cropping regions of southeast Australia SWAGMAN® Destiny was used to explore the likely yields of wheat sown after rice, and impacts on watertables and rootzone salinity, for a range of site and management conditions (Smith and Humphreys, 2001). Yields of non-irrigated wheat were higher for early sowing, and were reduced by the presence of a shallow saline watertable. Yields increased with frequency of irrigation, and late sown wheat required more irrigations to achieve the same yields as early sown wheat. Watertables were generally lowered when the wheat was not irrigated, and net recharge increased with irrigation frequency. Smith and Humphreys (2001) and Godwin et al. (2002) provide other examples of applications of SWAGMAN® Destiny.

10. Conclusions and recommendations

There are many reports of the evaluation and application of CERES Rice in tropical and subtropical Asia, and of CERES Wheat in temperate environments around the world. Most reports provide very little detail on determination of genetic coefficients, and the values used. Therefore genetic coefficients for commonly grown varieties of rice and wheat in the rice-wheat regions are not readily available. Where this information is reported, genetic coefficients have generally been determined from only one study, thus results of validations may be impaired by poorly derived genetic coefficients. Further, it is difficult to identify reports of true validation (using independently derived genetic coefficients) as opposed to less rigorous evaluation (using genetic coefficients derived from the same data set).

CERES Rice has generally performed well in terms of number of days to key phenological events and grain and biomass yield in studies from tropical, sub-tropical and temperate Asia. However there are few reports of it's ability to predict a wider range of parameters, and evaluations under water and N limiting conditions are few and suggest that the model does not perform well under stress conditions. With increasing emphasis on improving water and N use efficiency, and the move away from continuously ponded rice culture in many regions, the performance of CERES Rice needs further evaluation under conditions which attempt to save water and increase N use efficiency. The ability to simulate ammonium leaching needs to be included for the coarse textured soils of the rice-wheat region of northwest India, moreso with the current interest in moving away from puddled soils to alternative systems such as direct drilling and permanent beds. Evaluation of CERES Rice in the Australian rice growing region has been limited, and demonstrates the need for a chilling injury routine to simulate the effect of low temperatures on fertility. Such a routine has been developed, but it requires further testing, and possible modification in the light of recent understanding of the mechanisms of cold damage.

CERES Wheat has been evaluated in a wide range of environments across the world, but only in a few cases in sub-tropical environments of the rice-wheat areas of Asia. Evaluation in the sub-tropics has mostly been limited to phenology and grain and biomass yields, with reasonable ability to predict anthesis and maturity dates and grain yield, but not biomass yields. Results from other environments across the world have been mixed, reemphasising the importance of validating the model before applying (with refinements as required) it to the environment of interest. Incorporation of processes simulating ammonia volatilisation could be important in evaluating irrigation and N fertiliser management on high pH soils such as those in the rice-wheat regions of northwest India.

While the ability of models to simulate the performance of individual crops is very important, it is also desirable to evaluate the performance of cropping systems over the medium and long term. There has been only one study evaluating the performance of the CERES Rice-Wheat sequence model under the DSSAT framework. In that study the sequential model performed fairly satisfactorily in terms of yield prediction, but simulation of soil C and N changes was not realistic. The DSSAT/CERES Rice-Wheat sequence model needs to be evaluated against observations from rice-wheat systems for a range of locations and management. The results of long-term experiments could be useful for this purpose, however adequate data availability is often a problem.

The CERES models offer other advantages, including routines for readily examining the impact of climate change and CO_2 levels, while the MERES model adds the ability to predict methane emissions to CERES Rice.

SWAGMAN® Destiny is a potentially useful model for identifying sustainable management in environments affected by shallow watertables and salinity. It has been evaluated against only a few data sets in Australia and one study in Asia, and there are no reports on its evaluation and application in highly regarded publications. Results to date suggest that it performs well in simulating wheat growth, yield and soil water content in the rice-growing areas of southern Australia, however it has not been tested for wheat in other environments, or for rice. At present SWAGMAN® Destiny can only simulate monocultures, and it's usefulness will be greatly improved by incorporating the ability to simulate crop sequences.

There are many examples of the application of CERES Rice and CERES Wheat across Asia, but only a few applications for Australia. The models have been used most extensively in predicting the effect of various climate change scenarios on crop yields. Climate change can affect yields of rice and wheat through direct affects of changed weather (temperature, radiation, rain, wind) and carbon dioxide levels on the crop, and through indirect effects such as effects of changed weather on the incidence of pests and diseases, and on the requirement for and availability of water for irrigation. The effects vary with location and cultivar characteristics. Yields of rice and wheat are frequently reduced by increased temperature due to reduced duration, especially during grain filling. However increased temperature can also expand the geographically suitable regions for rice production, such as shifting the boundary for rice production in China further north. While increasing temperature generally reduces yields of both wheat and rice, this is often partially or fully compensated for by increasing carbon dioxide concentration. Negative impacts on yield can be reduced to varying degrees by strategies such as changing planting dates, increasing irrigation, and more heat tolerant cultivars. The results of the climate change modelling suggest that some of the biggest impacts could be reduced wheat yields in Pakistan and northwest India, reduced rice yields in Thailand, and variable effects depending on latitude in China and Japan. Aggarwal and Mall (2002) demonstrated that the impacts could vary from large positive to large negative impacts based on the uncertainty in the climate change and crop modeling predictions. The results suggest that climate change could have huge impacts on local and regional food security.

Other major applications of the CERES Rice and Wheat models have included yield forecasting, yield gap and yield trend analysis, evaluating agronomic management strategies, evaluation of cropping options in new locations, prediction of greenhouse gas emissions, pest and disease management, and informing government planning. However, the impact of the application of the models on decision making by farmers and their advisors and policy makers is generally less clear.

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Table 1. Minimum data required for operation and evaluation of CERES Rice and CERES Wheat (Hunt and Boote, 1994)

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)

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Table 2. Genetic Coefficients for the CERES Rice and Wheat

A. Rice	
P1	Time period in growing degree days (base 9°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°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} $kernortheastl^{-1}day^{-1}$)
G3	Tiller death coefficient. Standard stem + spike weight when elongation ceases (g)
PHINT	Thermal time between the appearance of leaf tips

Table 3. Data requirements for calibration and validation of SWAGMAN Destiny models (D. Smith, CSIRO Land and Water, Griffith, NSW, Australia, personal communication).

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a. Absolute minimum

Phenolgical date observations

- Date of Sowing
- Flowering
- Physiological maturity
- Grain yield

b. Additional information that will improve the calibration/validation &/or our confidence in it

i. Crop growth

- Biomass harvests, particularly at flowering and maturity
- LAI
- Grain moisture content
- Visual observations of the crop if it appears stressed in any way, especially insect damage, diseases, weeds, nutrient deficiency, others

ii. Water and salinity
- rainfall (dates and amounts)
- irrigations (dates and amounts)
- salinity of irrigation water
- soil water content, if available

iii. Paddock history
- when and what was the last crop?
- what was done with the stubble, e.g. burnt, incorporated

iv. Soil
- depth to watertable, if shallow (and salinity)
- soil type - local name if known, and/or description, e.g. self-mulching grey clay, red loam
- root length density, if available

v. Fertilizers
Some idea of fertiliser history for an indication of fertility index

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Table 4. Genetic coefficients for rice cultivars, grown in Asia and Australia, determined for CERES Rice

Rice	Cultivar type	Duration	Stature	Location	Soil	Coefficients							
						P1	P2O	P2R	P5	G1	G2	G3	Source
BR14	Indica	Short (130 d)	Semi-dwarf	Nashipur, Bangladesh	Sandy clay loam	560	11.5	200	500	45	0.026	1	Timsina et al., 1998
BR11	Indica	Medium (150 d)	Semi-dwarf	Nashipur, Bangladesh	Sandy clay loam	825	11.5	300	390	52	0.024	1	Timsina et al., 1998
Pant - 4	Indica			Pantnagar, India	Silty clay loam	830	11.4	160	300	35	0.03	1	Timsina et al., 1995
Masuli	Indica	Long	Semi-dwarf	Nepal		830	11.4	200	600	35	0.03	1	Timsina et al., 1997
Chaite-2	Indica	Short	Dwarf	Nepal		560	11.5	200	500	45	0.026	1	Timsina et al., 1997
IR52	Indica	short	semidwarf	Philippines		425	11.8	125	454	72	1	1	Hoogenboom et al., 1997
Jaya	Indica			Kerala, India	Loam	830	15	50	277	72.8	0.028	1	Saseendran et al., 1998
IR36	Indica	Short	Semidwarf	IRRI, Philippines		590	11.7	124	550				Alocilha & Ritchie, 1991
IR36	Indica	Short	Semidwarf	IRRI, Philippines		450	11.7	149	350	68	0.023	1	Hoogenboom et al., 1997
IR8	Indica			Pantnagar, India	Loam, silty clay loam	880	12.1	52	550	65	0.028	1	Timsina et a;., 1995
IR72	India	short	semidwarf	Philippines		400	12	100	580	76	0.023	1	Hoogenboom et al., 1997
Amaroo	Japonica		Semidwarf	Southern NSW, Australia	Mundiwa clay loam	370	14.5	750	85	80	0.026	1	Meyer et al., 1994
Calrose	Japonica		tall	Southern NSW, Australia	Mundiwa clay loam	325	14	600	92	75	0.025	1	Meyer et al., 1994
PR106	Indica			Punjab, India	Sandy loam	500	11.5	150	300	60	0.024	1	Pathak et al., 2003
China Early						100	12.4	130	332	55	0.025	1	Hoogenboom et al., 1997
China Late						100	12	166	328	55	0.025	1	Hoogenboom et al., 1997

Table 5. Genetic coefficients for spring wheat cultivars, grown in Asia and Australia, determined for CERES Wheat

Cultivar	Duration	Type	Location	Soil type	Climate	P1V	P1D	P5	G1	G2	G3	PHINT	Source
Kanchan	Medium (105 d)	Semi-dwarf	Nashipur, Bangladesh	Sandy clay loam	Sub-tropical	1.0	1.3	4.3	5.0	4.0	2.7	99	Timsina et al., 1998
Sowgat	Medium (108 d)	Semi-dwarf	Nashipur, Bangladesh	Sandy clay loam	Sub-tropical	1.0	3.0	4.0	5.5	4.5	2.7	97	Timsina et al., 1998
RR21	Short	Semi-dwarf	Pantnagar, India	Loam, silty clay loam	Sub-tropical	1.0	1.5	5.0	4.0	2.9	2.4	95	Timsina et al., 1996
RR21		Semi-dwarf	Nepal		Sub-tropical	1.0	1.5	5.0	3.5	2.9	2.4	90	Timsina et al., 1997
UP262	Medium	Semi-dwarf	Nepal	Loam, silty clay loam	Sub-tropical	1.0	3.0	5.0	4.0	2.9	2.4	90	Timsina et al., 1997
HD2009	Medium	Semi-dwarf	Pantnagar, India	Loam, silty clay loam	Sub-tropical	1.0	2.3	4.0	4.0	2.9	2.4	95	Timsina et al., 1996
HD2329	Medium	Semi-dwarf	Ludhiana, India	Sandy loam	Sub-tropical, semi-arid	0.5	2.5	3.5	2.5	2.9	4.0		Hundal and Kaur, 1997
HD2329	Medium	Semi-dwarf				0.5	3.2	2.6	3.4	3.5	4.2	95	Pathak et al., 2002
ANZA	Short	dwarf	Los Baños, Philippines	Clay	Tropical	0.0	3.4	2.0	3.5	2.7	4.4	95	Timsina et al., 1996
UPLW1	Short	dwarf	Los Baños, Philippines	Clay	Tropical	0.0	4.0	7.0	5.0	4.0	3.0	95	Timsina et al., 1996
UPLW3	Short	dwarf	Los Baños, Philippines	Clay	Tropical	0.0	3.5	7.0	5.0	4.0	3.0	95	Timsina et al., 1996
Janz	Long	Semi-dwarf	Southern NSW, Australia	Clay	Temperate, semi-arid	0.5	3.0	2.8	2.9	1.3	4.4	95	Smith et al., 2003
Yecora	Short	Dwarf	Southern NSW, Australia	Clay	Temperate, semi-arid	0.5	2.8	2.0	3.2	3.0	4.4	95	Smith et al., 2003
Bindawarra	long	Semi-dwarf	Southern NSW, Australia	Clay	Temperate, semi-arid	0.5	3.2	2.5	2.6	2.5	4.4	95	Smith et al., 2003

Table 6. Summary of validation of CERES Rice in Asia and Australia

Location	Soil	Climate	Cultivar	Model version	Anthesis (d) Pred.	Anthesis (d) Obs.	Maturity (d) Pred.	Maturity (d) Obs.	Grain (t/ha) Pred.	Grain (t/ha) Obs.	Straw (t/ha) Pred.	Straw (t/ha) Obs.	Reference
Pantnagar, India	Mollisol, silty clay loam	sub-tropical, humid	Pant-4	ver. 3.0	87-101	87-103	116-136	111-137	2.3-7.5	2.1-7.4			Timsina et al., 1995[a]
Nashipur, Bangladesh	Sandy clay loam	sub-tropical, humid	BR 14	ver. 3.0	68-70	68-74	100-105	100-104	2.5-8.8*	2.7-6.2			Timsina et al., 1998[a]
			BR 11	ver. 3.5	88-95	89-102	122-131	121-131		3.3-7.4			
Kerala, India**	Sandy loam		Jaya	ver. 3.0	74-87	71-80	111-124	105-122	3.3-6.8	3.3-6.5	5.2-7.8	4.2-5.8	Saseendran et al., 1998[a,b]
Kerala, India	Sandy loam	Humid tropics	Jaya	ver. 3.0					3.5-7.2	3.3-5.2			Rao et al., 2002[b]
			Jyothi	ver. 3.0					4.5-7.7	4.6-6.4			
			Triveni	ver. 3.0					3.9-6.0	4.3-5.8			
India			7 cultivars		36-85	37-86			2.8-9.4	2.8-8.9			Mall and Aggarwal, 2002[c]
Thailand	Clayey, fine	Tropical	RD23, NSPT	Ver. 2			99-105	90-93	4.4-4.85	4.23-4.53	3.49-3.83	4.12-4.89	Tongyai, 1994
North, Central, and NE Thailand		Tropical to sub-tropical	Non-photoperiod sensitive	ver. 2.0					1.2-6.5	2.5-5.8			Jintrawat, 1995[d]
NE Thailand (Ubon)			Photoperiod sensitive		65-180	54-198							
Nanchang, China		sub-tropics to warm temperate	Guang Lu Ai 4				82	81	5.2	4.9	7.3	6.7	Salam et al., 2002[e]
Moroika, Japan		cool temperate	Sasanishiki				149	145	6.5	6.4	11.5	5.6	
Los Banos, Philippines	clayey	tropical, humid	IR36, IR50, IR72				104	112	7.3	5.8	9.3	-	
Los Banos, Philippines	clayey	Tropical, humid	IR 43	upland rice	94-99	93-100	127-129	123-134					Alocilja and Ritchie, 1991
			UPLRi 5		93-98	91-100	117-121	116-125					
			UPLRi 7		84-92	88-93	115-119	112-123					
Los Banos, Philippines		Tropical	IR 72 and others	MERES					2.8-5.0^^	2.4-6.0	6.4-14.2#	8.0-14.2^^#	Mathews et al., 2000[f]
Hangzhou, China		Sub-tropical	Chungiang and others						2.6-6.8	4.7-5.8	6.0-15.0#	8.1-15.0#	
Los Banos, Philippines	clayey	Tropical, humid									4.5-12.8	4.8-13.5	Godwin et al., 1990
Java and Sumatra, Indonesia	clayey	Tropical, humid	IR 36						2.7-6.9*	2.6-7.8*			Amien et al., 1996
			IR 42						2.2-7.5	2.1-7.5			
MIA, NSW, Australia	clay loam or clayey	Temperate, semi-arid	Calrose	ver. 2.1					3.7-10.0	2.8-8.2			Godwin et al., 1994
				ver. 2.1c					2.0-10.0	2.0-10.0			
MIA, NSW, Australia	clay loam or clayey	Temperate, semi-arid	Amaroo	ver. 2.1c					4.6-10.3	2.0-9.5	8.6-22.2#	5.0-22.9#	Meyer et al., 1994[g]

*across cultivars and/or locations
#total above-ground biomass yield
^9 of 18 treatments were sprinkler irrigated and didn't simulate well
^^3 outliers due to mid-season drainage and didn't simulate well
[a]several N rates and 2 water regimes
[b]7 transplanting dates under rainfed
[c]11 locations with varying soils and climate from north to south India (treatments ranged from 2 to 23 across sites)
[d]2 years for 6 sites for non-photoperiod sensitive and 3 years for one site (with 8 transplanting dates) for a photoperiod sensitive cultivar
[e]early season rice for Nanchang, single season rice for Morioka, and dry season rice for Los Banos
[f]treatments included frequency and timing of drainage, cultivars, and amounts and type of inorganic and organic amendments
[g]18 treatments from a range of experiments

Table 7. Validation of CERES Rice for additional characters.

Characters	Cultivar	Location	Predicted	Observed	Reference
Emergence (d)	IR43	Los Banos, Philippines	4	4.0-8.0	Alocilja and Ritchie, 1991
	UPLRi5		4	4.0-6.0	
	UPLRi7		4	4.0-8.0	
LAI	Many	India	1.7-6.1	2.2-8.0	Mall and Aggarwal, 2002
Grains/m2		India	13,000-30,000	15,000-31,000	Mall and Aggarwal, 2002
		Kerala, India	14,679-21,900	16,413-21,899	Saseendran et al., 1998[a]
		Thailand	4,500-24,500	3,000-21,000	Jintrawat, 1995
Grain weight (g)		Thailand	.028-.030	.029-.030	Jintrawat, 1995
		Thailand	.022-.023	.014-.027	Jintrawat, 1995
HI		Nanchang, China	0.42	0.43	Salam et al., 2002
		Moroika, Japan	0.36	0.53	
		Los Banos, Philippines	0.44	-	
Tatal evaporation (mm)		MIA, NSW, Australia	1084	1062	Meyer et al., 1994
N loss (kg/ha)		Los Banos, Philippines	6.0-58.0	5.0-49.0	Buresh et al., 1991; Godwin et al., 1990
Root biomass (t/ha)		Los Banos, Philippines	0.8-1.5	0.8-2.2^^	Mathews et al., 2000
CH_4 emissions		Los Banos, Philippines	0-450	0-480	Mathews et al., 2000
(kg CH_4-C/ha)		Maligaya, Philippines	150-450	125-570	
		Hangzhou, China	30-200	70-360	
Total N uptake (kg/ha)			45-175*	48-175	Timsina et al., 1998[a]
			40-145	35-150	Godwin et al., 1990
			89-249	34-205	Meyer et al., 1994[b]

^^3 outliers due to mid-season drainage

[a]several N rates and 2 water regimes

[b]18 treatments from a range of experiments

*across cultivars and/or locations

Table 8 . Summary of validation of CERES Wheat in Asia and Australia

Location	Soil	Climate	Cultivar	model version	Anthesis (d)		Maturity (d)		Grain yield (t/ha)		Above-ground biomass yield (t/ha)		Kernal wt. (mg)		Reference
					Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	
Pantnagar, India	Mollisol, silty clay loam	sub-tropical, humid	RR 21 HD 2009	ver. 3	66-105	62-100	99-140	98-146	3.3-5.5	3.1-5.5					Timsina et al., 1995[d]
Los Banos, Philippines		humid, tropics	UPLW3 UPLW1 ANZA	ver. 3					1.7-3.3	1.5-2.9					Timsina et al., 1995
Nashipur, Bangladesh	Sandy clay loam	sub-tropical	Sowgat Kanchan	ver. 3.5	78-82*	77-80*	111-115*	107-117*	1.0-4.9*	0.9-5.2*					Timsina et al., 1998[e]
Ludhiana, India	Sandy loam	sub-tropical, semi-arid	HD 2329	ver. 2.1	82-101	79-105	110-143	114-142	2.7-5.5	3.0-5.2	9.6-14.5	7.8-13.2	32.5-45.6	29.2-42.7	Hundal and Kaur, 1997[a]
Amritsar			HD 2329	N.A.					4.2-4.8	3.8-4.8					Nain et al., 2002[b]
Bhopal									1.5-1.9	1.6-1.8					
Jaipur									2.2-2.5	2.0-2.6					
Lucknow									2.2-2.4	2.0-2.5					
Faridabad									3.6-4.1	3.5-4.2					
Patna									2.4-2.8	2.4-2.8					
Many locations in world, including India, Bangldesh, and China				N.A.					1.5-6.8	1.1-7.7	4.8-17.5	2.5-27.5			Heng et al., 2002[c]
southern NSW,	Loam	semi-arid	Yecora,	ver. 3					5.5-5.7	5.5-5.9					Smith et al., 2003
Australia	Clay	temperate	Janz,						3.4-4.1	3.4-4.0					
	Clay loam		Bindawara						4.3	4.4					

*across cultivars

[a]8 years with 3 to 5 sowing dates; irrigated

[b]genetic coefficients of HD2329 as described by Hundal and Kaur (1997) used at all sites; observed yields are district average yields and simulated yields are potential yields

[c]under irrigated condition

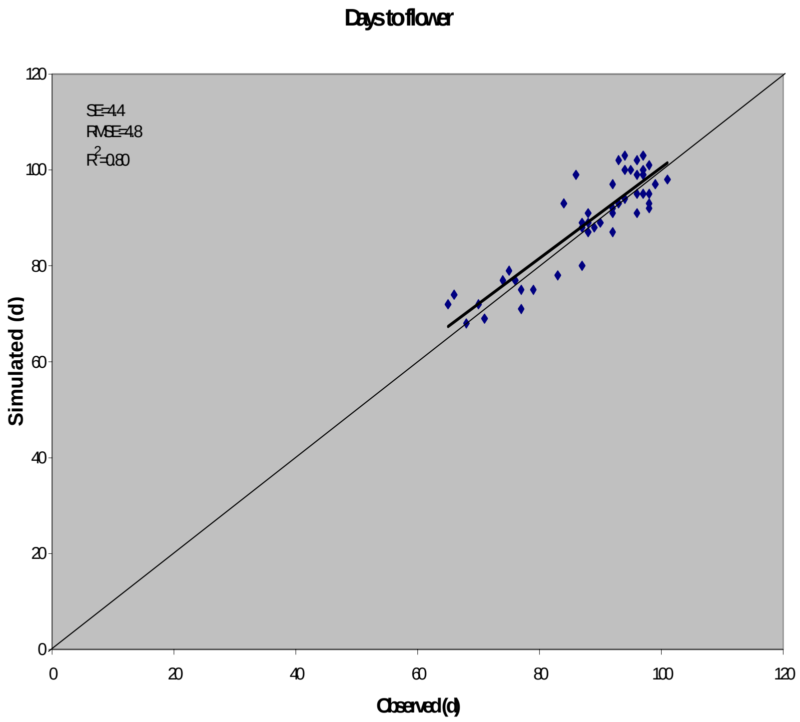
[d]observed LAI=2.4-3.7;predicted LAI=1.6-4.6

[e]observed total N uptake (kg/ha)=17-124;predicted total N uptake=21-125

Table 9. Summary of applications of CERES Rice and CERES Wheat in Asia and Australia

Application type	Crop	Countries	References
Yield forecasting	Wheat	Australia	Stephens et al. (1989); McMahon, 1983
Yield gap/trend analyses	Rice	Thailand, Philippines, southern Vietnam, Nepal, India,	Jintrawat (1995); Pinnschmidt et al. (1997); Timsina et al. (1996, 1997); Saseendran et al. (1998a,b); Sherchand (1998); Aggarwal et al. (2000a); Boonjung (2000); Pathak et al. (2003)
	Wheat	Nepal, India	Timsina et al. (1996, 1997); Sherchand (1998); Aggarwal et al. (2000a); Pathak et al. (2003)
Strategic decision making and planning	Rice	Bangladesh, Philippines, India, China	Buresh et al. (1991); Singh and Thornton (1992); Timsina et al. (1998); Heng et al. (2000)
	Wheat	Bangladesh	Timsina et al. (1998)
Tactical management strategies	Rice	India, Nepal, Bangladesh, Philippines, Thailand	Singh and Thornton (1992); Timsina et al. (1995, 1997)
	Wheat	India, Nepal, Bangladesh, Thailand	Timsina et al. (1995, 1997, 2001); Saseendran et al. (1998a,b); Hundal and Kaur (1999), Boonjung (2000)
Climate change studies	Rice	Australia, Bangladesh, China, India, Indonesia, Japan, Nepal, Philippines, Thailand	Bachelet et al. (1993); Banchelet and Gray (1993); Singh and Ritchie (1993); Baer et al. (1994); Escano and Buendia (1994); Karim et al. (1994); Luo et al. (1995); Singh and Padilla (1995); Buan et al. (1996); Tongyai (1994); Seino (1994, 1995); Zhiqing et al. (1994, 1995); Amien et al. (1996); Hundal and Kaur (1996); Timsina et al. (1997); Hundal et al. (1998); Lal et al. (1998); Saseendran et al. (2000); Aggarwal and mall (2002)
	Wheat	Australia, India, Japan, Nepal, Pakistan,	Baer et al. (1994); Qureshi and Iglesias (1994); Rao and Sinha (1994); Seino (1994, 1995); Hundal and Kaur (1996); Timsina et al. (1997); Lal et al. (1998);
Prediction of greenhouse gas emissions	Rice	Australia, China, India, Indonesia	Matthews et al. (2000c), Grace (2002)
Pest and disease management	Rice	Philippines, Thailand, Vietnam	Pinnschmidt et al. (1990, 1995)
Aiding government policy	Rice	India, Indonesia, Taiwan	Chou and Chen (1995); Amien et al. (1996); Aggarwal et al. (2000b)

Figure 1. Simulated and observed days to anthesis and maturity of rice across a range of experiments in Asia
(data from Alocilja and Ritchie, 1991; Seino, 1991, Timsina et al., 1995, 1998; Saseendran et al., 1998b; Salam et al., 2003)



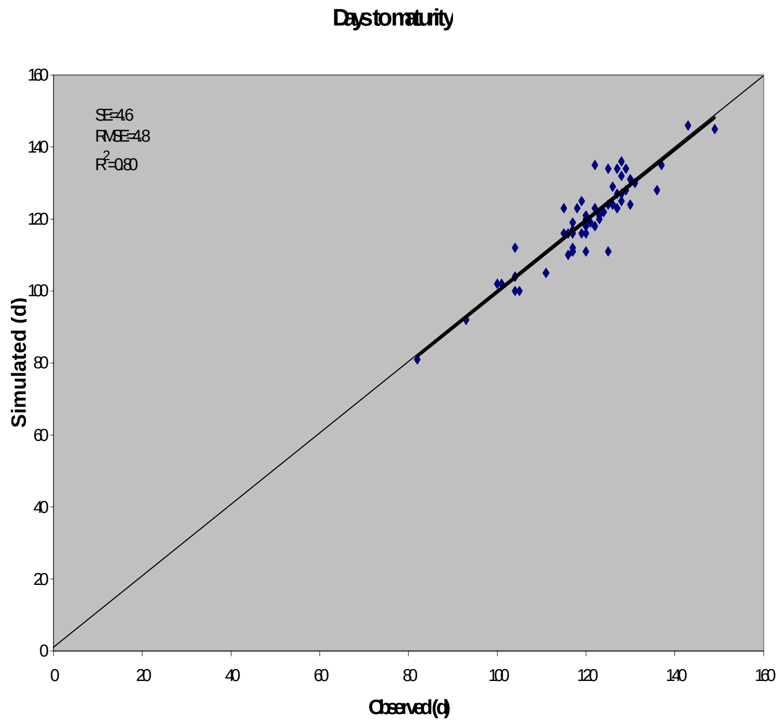


Figure 2. Simulated and observed grain and biomass yields of rice across a range of experiments in Asia and Australia

(data for grain yield from Alociljha and Ritchie, 1991; Rao et al., 1993, 1994; Saseendran et al., 1993, 1994; Meyer et al., 1994; Jintrawat, 1995; Seino, 1995; Amien et al., 1996; Timsina et al., 1995, 1996, 1998; Mathews et al., 2000; Mall and Aggarwal, 2002; Salam et al., 2003, and for biomass yield from Alociljha and Ritchie, 1991; Saseendran et al., 1993, 1994; Mathews et al., 2000; Salam et al., 2003)

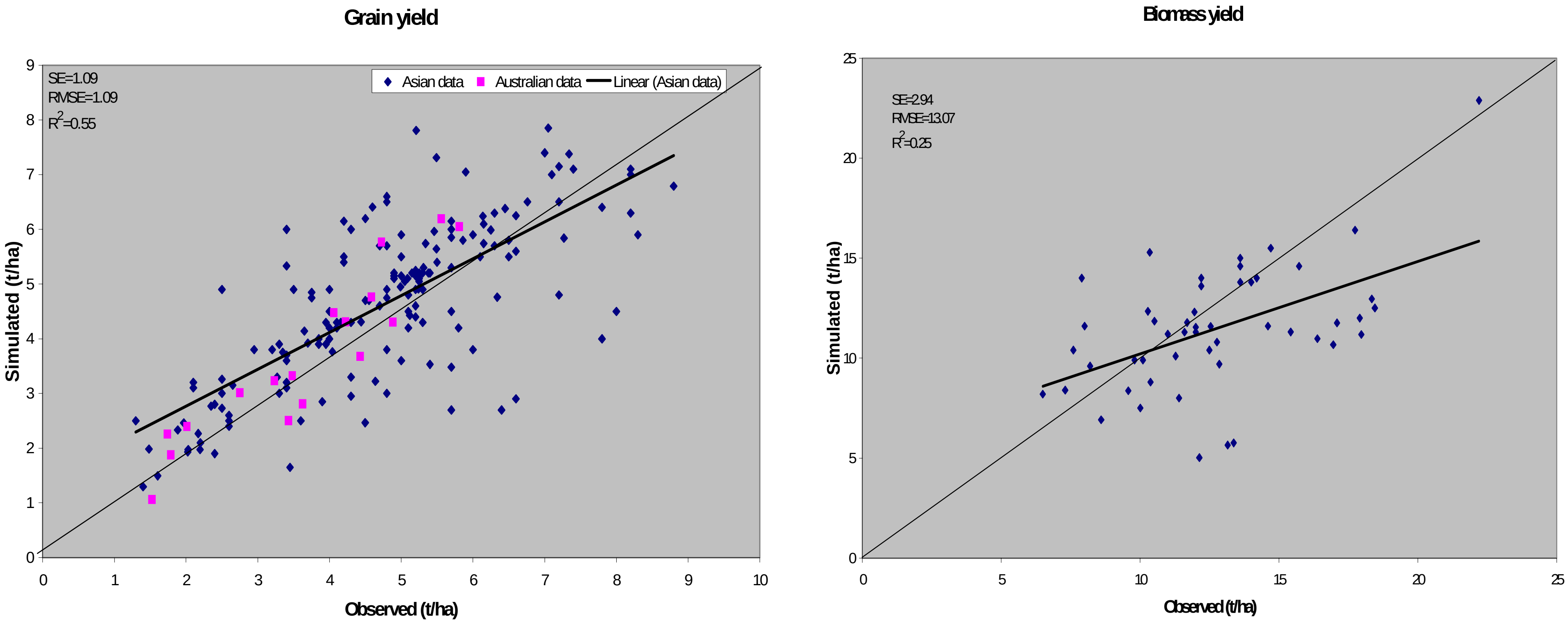


Figure 3. Simulated and observed total N uptake (kg/ha) of rice for one study each in Asia and Australia.
(data from Meyer et al., 1994; Timsina et al., 1998)

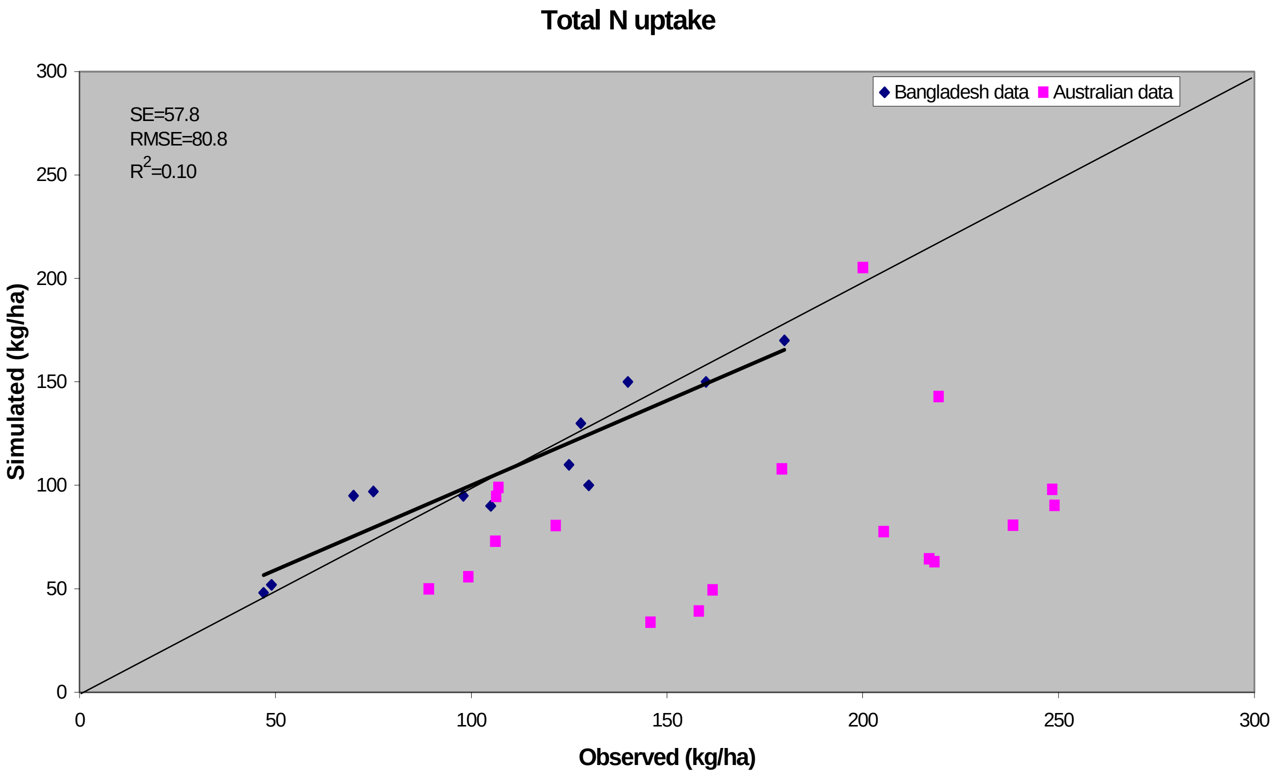
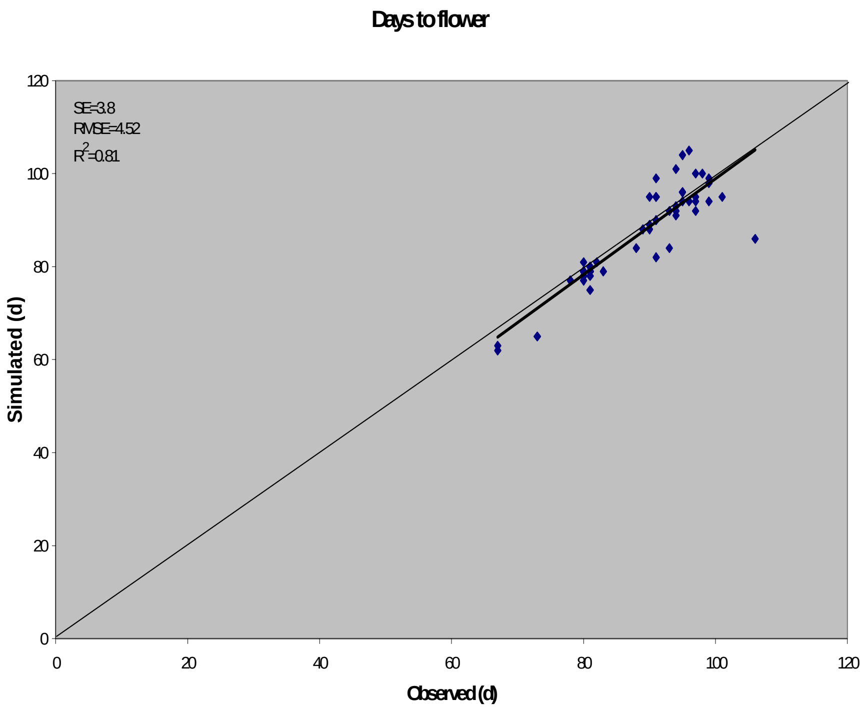


Figure 4. Simulated and observed days to anthesis and maturity of wheat across a range of experiments in Asia
(data for anthesis from Hundal and Kaur, 1997 and Timsina et al., 1998, and for maturity from Seino, 1995; Timsina et al., 1995, 1998 and Hundal and Kaur, 1997)



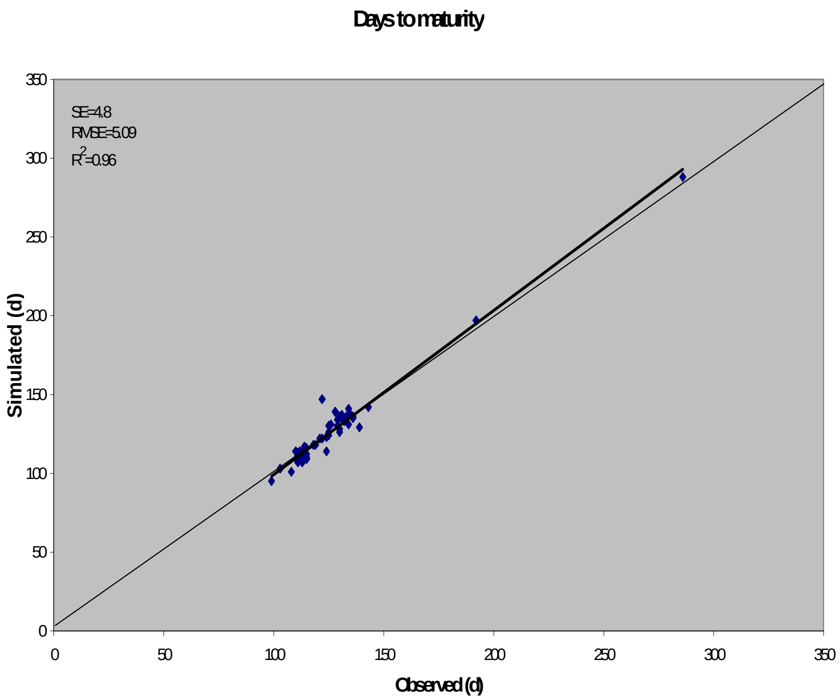


Figure 5. Simulated and observed grain and biomass yields of wheat across a range of experiments in Asia and Australia (data for grain yield from Seino, 1995; Timsina et al., 1995, 1998; Hundal and Kaur, 1997; Godwin et al., 2002; and for biomass yield from Hundal and Kaur, 1997 and Heng et al., 2000).