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Applications of CERES-Rice and CERES-Wheat in Research, Policy and Climate Change Studies in Asia: A Review

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Abstract: Crop models have many current and potential uses for improving research understanding, crop management decisions, policy planning and implementations and adapting to current and future climate change. A comprehensive literature review was done to synthesize and assess the various applications of CERES-Rice and CERES-Wheat in Asia, with a view to apply the "lessons learnt" to make the research and development more effective. Examples are given of the use of CERES-Rice and CERES-Wheat for yield gap and yield trend analyses, for improving overall crop management by making appropriate planting decisions, devising improved cultural practices and developing improved nitrogen, water and pest management strategies. In policy, the models are used to predict the impacts of climate change on crop productivity and to assist government in the strategic decision making and planning. Among all, predicting the impacts of various climate change scenarios on crop yield and water use and identifying adaptive strategies to the changed climate is the most important area of application dominating the literature. Most climate change studies revealed that increased temperatures decreased growth duration and yield and water use of both crops, but with more adverse effect on wheat. Increased CO_2 concentrations increased yield of both crops, but the positive effects of CO_2 could be offset by negative effects of increased temperatures and vice versa. Increased rainfall increased evapo-transpiration of rice and increased yield, especially in rainfed areas. Adverse climate change would result in larger decreases in yield in low- and smaller decreases in mid- to high-latitudes, but the severity of blast disease would be high in cool sub-tropical and temperate and low in warm humid tropical areas. Some of the biggest impacts of climate change would be reduced wheat yields in Pakistan and northwest India and reduced rice yields in Bangladesh and Thailand. Effects of climate change in China and Japan were variable depending on latitude. Early planting, irrigation and selection and breeding cultivars for adaptation to climate change were some of the adaptive strategies for both crops. The literature reveals that despite a great deal of current use of these models by the scientific community, frustratingly, there is neither any evidence in the use or uptake of the outputs of these models by farmers, governments, or other clients and stakeholders, nor in the development or adoption of revised management guidelines in Asia. Further, studies on the impacts and adaptation of climate change revealed that there is very little evidence that the model results have really been used by any stakeholders or policy makers in the state or national levels in the countries of Asia. One of the major limitations for the scientific community is unavailability of quality input data on weather, soil and crop management for model evaluation. Nevertheless, we believe that the use of CERES will play an increasingly important role in improving research understanding and decision making in crop management, in assisting policy and in preparing and adapting to the current and future climate change. Hence, while recognizing the potential limitations, we suggest that efforts be continued to facilitate the uptake of the model results by farmers, stakeholders and the policy makers if CERES rice and wheat have to make contributions in the real world.

Key words: CERES-Rice, CERES-Wheat, model applications, adaptive strategies for rice and wheat, crop management

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Introduction

Rice and wheat are the two most important crops for food security in most countries of Asia. They are grown on approximately 231 Mha and produce about 789 Mt grain in Asia. Country averages for 5 years (2000-2004) reveal that rice and wheat together are grown on approximately 69 and 52 Mha and produce 200 and 269 Mt grain, respectively, in China and India, the two largest rice and wheat producing countries in Asia (http://www.fao.org/waicent/portal/statistics_en.asp). These crops are also grown in annual sequences on approximately 13 Mha in the Indo-Gangetic Plains of south Asia and 3.4 Mha in the Yangtse River basin in China and together contribute to about 72 and 85% of total cereal production and 56 and 60% of total national intake (Timsina and Connor, 2001; Dawe *et al*., 2004). For that reason, many national programs in Asia have put large research efforts to improve the productivity and sustainability of rice and wheat production systems. Despite such efforts, rice and wheat yields in the many Asian countries have stagnated or declined, especially in the rice-wheat (RW) systems of south Asia and there are large gaps between climatically and genotypically determined potential yields and farmers' yields (Timsina and Connor, 2001; Ladha *et al*. 2003). The ability to sustain yields, let alone increase yields in pace with population growth, is threatened by impending water scarcity and by soil degradation, climate change and pollution of ground and surface waters and the atmosphere. Understanding the causes of decline, and closing the gaps, in rice and wheat yields requires a great deal of effort in terms of improving the crop management such as improving cultural practices, choice of varieties, fertilizer and nutrient and water use. Such efforts also require evaluations of risks for yield response to long-term historic weather records and optimisation of planting date and density, row spacing and water and nutrient management strategies in various soil types (Timsina and Connor, 2001). Such management and optimisation is especially important and remains a challenge for these crops, because the dominant characteristic of the system where these crops are generally grown is the repeated transition from the anaerobic conditions for rice to aerobic conditions for wheat (Timsina and Connor, 2001).

Crop models provide a means to quantify the effects of climate, seasonal weather conditions, soil, management and genotype and their interactions on crop growth, yield, resource use efficiency and environmental impacts (Boote *et al*., 1996). They can be used to quantify the gaps between potential and actual yields, to evaluate management options and to determine likely environmental impacts. They can also be used to forecast yields prior to harvest and extrapolate the results conducted in one season or location to other seasons, locations, or management. A particular strength of crop models is their ability to quantify variability of crop performance due to variability in seasonal weather conditions and to predict the long-term impacts of climate change and land use options. Thus models can potentially provide a unique means of quantifying the potential impacts of climate change on crop performance and water use requirement and in the evaluation of adaptation strategies.

There are various rice and wheat models around the world, of which the ones developed by the three main groups have dominated their evaluations and applications in Asia. These groups are: decision support system for agro-technology transfer/crop estimation through resource and environment synthesis (DSSAT/CERES) largely developed under the international benchmark sites network for agro-technology transfer (IBSNAT) project in USA (Jones *et al*., 2003); Dutch-origin models, especially ORYZA 2000 and its predecessors for rice, developed under the system analysis for rice production (SARP) project jointly by Wageningen University and Research Centre (WUR) and the international rice research institute (IRRI), Philippines (Bouman *et al*., 1996, 2001); and agriculture production system simulator (APSIM) models (McCown *et al*., 1996), launched and developed jointly by various organizations in Australia under the name of Agriculture Production Research Unit (APSRU) Group. While wheat models developed by the Dutch group have also been sparsely used in Asia and there has been a recent addition of ORYZA2000 within the APSIM suite of models (Zhang *et al*., 2004), the literature on the evaluations and applications of rice and wheat models in Asia largely dominates the ones developed by the IBSNAT group. Hence, while we duly recognise the contributions of the Dutch and Australian models in Asia, this review focuses on the applications of CERES-Rice and CERES-Wheat only simply because they have been evaluated and applied over a wide range of environments in Asia (Timsina and Humphreys, 2006) and are not specific to any particular location or soil type. Further, while the current review identifies many areas of applications of these models in Asia, the discussion in this review is skewed towards the applications in climate change due to the dominancy of such applications in the literature.

The CERES-Rice and CERES-Wheat models simulate crop growth, development and yield, taking into account the effects of weather, genetics, soil water, carbon and N and planting, irrigation and N fertilizer management (Ritchie *et al*., 1998). These models can also be run in sequence under the DSSAT system, offering the ability to evaluate options for increasing yield and water-and N-use efficiency of RW systems (Timsina *et al*., 1995, 1996). Timsina and Humphreys (2006) reviewed the performance of CERES-Rice and CERES-Wheat in the RW areas of Asia and Australia and concluded that both models have generally performed well in predicting the dates of phenological events and grain and biomass yields, but CERES-Wheat performed generally better in Australia than in Asia. Those results highlight the need of proper calibration and evaluation of the models in the environment of interest before applying them to inform management guidelines or policy.

There are many reports of applications of CERES rice and wheat models to investigate a range of issues from crop management to yield gap analysis to the impacts of climate change on yields of rice and wheat crops in Asia. The continuing development of DSSAT (now DSSAT 4.0) and the various input and outputs files, has facilitated the calibration, validation and application of these models across the world, including Asia (Tsuji *et al*., 1994a,b,c; Porter *et al*., 2003; Hoogenboom *et al*., 2004). The objective of this paper is to comprehensively review and synthesize the various applications of CERES-Rice and CERES-Wheat in Asia and elucidate the "lessons learnt" that can be applied in the future to make research and development more efficient and cost-effective.

Major Categories of Applications

Various authors have offered various reasons for building and applying crop models. Whisler *et al*. (1986) summarised reasons into three broad categories: (i) as aids in interpreting experimental results, (ii) as agronomic research tools, or (iii) as agronomic grower tools, while Boote *et al*. (1996) categorised them into other three categories: (i) research knowledge synthesis, (ii) crop system decision management and (iii) policy analysis. Mathews and Stephens (2002) further grouped them into other three categories: (i) as tools in research, (ii) in decision support and (iii) in education and training. Based on the types of applications reviewed and on our own experiences, we have also categorised the applications of CERES-Rice and Wheat into three broad categories: (1) improving research understanding (2) improving decisions in crop management and (3) informing policy and strategic planning. These three major categories are broken down into 8 major application types (Table 1). Of all, impact of climate change on crop performance is the main type of applications dominating the literature. The next most popular applications relate to yield gap and long-term yield trend analyses and to evaluation of crop management options, such as N, planting and pest management.

Table 1: Summary of applications of Ceres-Rice and CERES-Wheat in Asia

Application type	Crop	Countries	References
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.* (2003a)
	Wheat	Nepal, India	Timsina *et al.* (1996, 1997); Sherchand (1998); Aggarwal *et al.* (2000a); Pathak *et al.* (2003a)
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	Bangladesh, China, India, Indonesia, Japan, Nepal, Philippines, Thailand	Bachelet *et al.* (1993); Banchelet and Gray (1993); Singh and Ritchie (1993); 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, 1999); 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	India, Japan, Nepal, Pakistan,	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 emission	Rice	China, India, Indonesia	Matthews *et al.* (2000b)
Pest and disease management	Rice	Philippines, Thailand, Vietnam	Pinnschmidt *et al.* (1990, 1995); Luo *et al.*, 1998
Aiding government policy	Rice	India, Indonesia, Taiwan	Chou and Chen (1995); Amien *et al.* (1996); Aggarwal *et al.* (2000b)

Improving Research Understanding

Yield Gap Analyses

Crop models can play an important role in the estimation of yield potential and yield gaps at site, regional and national levels, in the identification of reasons for the gaps and in the evaluation of management options for closing those gaps. An early application of CERES-Rice in terms of yield gap analysis in Asia is from Thailand, where Jintrawat (1995) used the model ver. 2.0 in north (Chiang Mai) and northeast (Khon Kaen) Provinces to predict the long-term yields (with 20 kg N ha^{-1} representing farmers' practice and 40 kg N ha^{-1} representing N "suggested" for potential yield) and identify yield gaps for those provinces. Long-term simulated potential yields for Chiang Mai (4.5 to 5.0 t ha^{-1}) and Khon Kaen (2 to 3.5 t ha^{-1}) were higher by 0.5 t ha^{-1} than with farmers' practice, which in turn were higher than for provincial yields by 0.4 t ha^{-1} (Khon Kaen) and 1 t ha^{-1} (Chiang Mai). The yield gaps between long-term average provincial and simulated for farmers' practice were due to losses caused by insects, diseases, rodents and lodging, which the model cannot account for. Another such application is from three countries in SE Asia, where Pinnschmidt *et al.* (1997) estimated weather-limited (potential) and weather plus N-limited (attainable) rice yields using ver. 2.1 and compared them with established yield trends. They also used a simple empirical approach based on fertilizer N and soil organic matter (SOM). The gap between observed and predicted attainable yields averaged about 35% in the Philippines, 45% in Vietnam and 55% in Thailand, mainly due to N limitation in Thailand and to water deficit, pest and diseases and low SOM and low soil organic N (SON) in the other two countries.

In other studies with model ver. 3.5, Timsina *et al*. (1997) and Sherchand (1998) reported gaps between potential and water and N-limited yields of 3.5 to 5.0 t ha^{-1} for rice and of 1.5 to 5.5 t ha^{-1} for wheat at various sites in Nepal. Likewise, Timsina *et al*. (1996) also used ver. 3.5 to estimate potential yields of rice and wheat from 1979 to 1992 for a RW system at Pantnagar, India. At that site, simulated rice yields with 150 kg N ha^{-1} varied from 4 to 8 t ha^{-1} and were 0.5 to 2 t ha^{-1} higher than with 120 kg N ha^{-1}. In wheat, however, yields at 150 and 120 kg N ha^{-1} were similar, varying from 4.5 to 5.7 t ha^{-1}. The study suggested considerable gaps between potential and research station yields for rice, but only small gaps for wheat. With ver. 3.0 also, Saseendran *et al*. (1998b) reported very large yield gaps for Kerala in south India. Using ver. 3.5, Aggarwal *et al*. (2000a) reported very large gaps of ~8 t ha^{-1} for a RW system in Delhi. In a recent study, using ver. 4.0, Timsina *et al*. (2004) reported that the gap between potential and on-station yields ranged from 28 to 38% and that between the potential and on-farm yields ranged from 48 to 68% for three RW sites in northwest India. All these yield gap analyses studies suggest that there is plenty of scope to improve the farmers' yields by adopting suitable water and N management strategies.

Yield Trend Analyses

Simulation of long-term yield trends requires the ability to address issues related to carryover of water, SOM and nutrients between each phase of the cropping system. In such an endeavour, Timsina *et al*. (1996) used the sequential mode of DSSAT ver. 3.5 to predict yield trends of rice and wheat over 20 years for a RW system with 120 and 0 kg N ha^{-1} applied to each crop at Pantnagar, India. Rice yields decreased over 20 years, especially after year 11, with greater decline for 0 than 120 kg N ha^{-1}. Wheat yields, on the other hand, consistently increased over time, more so with 120 kg N ha^{-1} (Timsina *et al*., 1995, 1996). Linear regressions of year against simulated yield confirmed significant trends in rice yield decline and wheat yield increase. Regressions of year against simulated SON and simulated soil organic carbon (SOC) for 120 kg N ha^{-1} also showed steep decreases in SOC and SON over time, suggesting that the decline in rice yields was due to declining SOC and SON. However, the rate of decline was unrealistically high. The latest version of DSSAT (ver. 4.0) has a more comprehensive SOM routine based on CENTURY (Gijsman *et al*., 2002) which needs to be tested for RW systems using data from long-term field experiments.

Aggarwal *et al*. (2000a) also used CERES to compare predicted and measured yield trends for rice and wheat over 1980 to 1995 for several districts in northwest India. Over that time frame, rice yields declined over time in five and increased in two districts, while wheat yields increased in all districts, but at a slower rate in recent years compared with the previous decade. Although they did not use the sequential mode of DSSAT, both models, after resetting the initial conditions prior to each season, simulated well the decline in rice and increase in wheat yields similar to observed yield trends in a long-term experiment in Ludhiana, Punjab.

Pathak *et al*. (2003a) also compared measured district level average yields of rice and wheat with the potential yields predicted by CERES for several districts over 1985 to 1999 in India. The district level recorded rice yields varied from 2.1 t ha^{-1} (Raipur) to 5.6 t ha^{-1} (Ludhiana), while wheat yields varied from 1.0 t ha^{-1} (Raipur) to 4.3 t ha^{-1} (Ludhiana). Simulated potential rice yields during the same period, on the other hand, ranged from 7.7 t ha^{-1} (Raipur) to 10.7 t ha^{-1} (Ludhiana), while simulated potential wheat yields ranged from 5.2 t ha^{-1} (24-Pargana) to 7.9 t ha^{-1} (Ludhiana). The average change in potential rice yield ranged from –0.12 t ha^{-1} yr^{-1} (Delhi) to 0.05 t ha^{-1} yr^{-1} (Kanpur), with significant trends for rice yield decline in 4 out of 9 districts. The trend for potential wheat yield was not significant for any district and ranged from –0.07 t ha^{-1} yr^{-1} (Delhi) to 0.04 t ha^{-1} yr^{-1} (Faizabad and Pantnagar).

Despite such use of CERES for yield trend analyses in south Asia, Matthews and Stephens (2002) emphasized two major limitations of using crop simulation models for analysis of long-term trends. Firstly, cropping system models have not yet been adequately validated for a long enough time-span to determine their ability to simulate long-term behaviour, partly due to lack of good quality long-term data sets. Secondly, most crop models, including those in DSSAT, have been developed to describe growth and soil processes over one season and the processes simulated may not be adequate to represent the long-term behaviour of cropping systems.

One of the main objectives of using crop models is to help farmers through focussing research activities on the major factors limiting yield and to assist regional and national governments in planning and policy making and in prioritising the research and development activities. The applications of CERES for yield gap and yield trend analyses reported herein can potentially help in improving the research understanding by studying and managing the yield-limiting or yield-reducing factors. However, frustratingly, there is no evidence to date of use or uptake of the outputs of these models by farmers, governments or other clients and stakeholders in Asia. Nevertheless, we are optimistic that crop modelling will become an increasingly important tool for the study of long-term trends and sustainability issues in various crops, simply because there are no other reasonable approaches capable of capturing the complexity of interactions between the many processes involved in crops and cropping systems.

Improving Crop Management

To raise yields and/or increase resource-use efficiency, identification of the causes of low yields as well as improvement in crop management would be required. Crop models can be used strategically to evaluate management options and in real time, to guide decision making such as irrigation and N management. CERES have been used to evaluate management strategies such as sowing or transplanting dates, planting geometry, N and water management, although applications to date have tended to affirm current process understanding and developing recommended practices.

Nitrogen Management

Nitrogen is the major nutrient limiting rice and wheat yields and is used inefficiently, especially in rice. Nitrogen from a soil can be lost through leaching, volatilization and denitrification. Losses from all these processes vary in magnitude depending on the prevailing weather, stage of crop growth and water and N management and it is difficult or even inappropriate to recommend a single fertilizer strategy that is optimum in all seasons. As a result, there is often mismatch between supply and demand of N, thus reducing yields and causing atmospheric and ground water pollution. Crop models can potentially provide a way of assessing the long-term risk of N management options for the range of likely seasonal conditions.

An earlier example of use of CERES-Rice in N management was reported by Buresh *et al*. (1991), who found consistently higher predicted N response by rice for 15 January transplanting whereas NH_3 loss was greater for 15 July transplanting in Philippines. Another example is by Singh and Thornton (1992), who investigated the effect of N management on clayey and sandy soils on yield and N leaching in Thailand with 25 years of weather data. Simulated rice yields were lower with 50 kg urea-N ha^{-1}, compared with 100 kg urea-N ha^{-1}. Green manure at 4 t ha^{-1} could be substituted for 40 kg urea-N ha^{-1} without any yield loss, but simulated N losses from green manure could be as high as from urea. Simulated leaching losses were considerably higher on a sandy than on a clayey soil and in the latter, the losses were similar for all treatments. Singh and Thornton (1992) also compared the effect of urea application methods (broadcasting into 5 cm of floodwater, incorporation into soil without floodwater with a mixing efficiency of 30% and deep-point placement without floodwater with a mixing efficiency of 95%, with the floodwater in the two latter cases raised to 5 cm depth shortly after fertilizer application) on N losses and N-use efficiency in puddled transplanted rice in the Philippines. The model predicted rapid transformations in the floodwater within two days of urea application in the broadcast and moderately incorporated treatments, but little fertilizer N moved into the floodwater in the deep-placed urea treatment. The simulated increase in algal growth and photosynthesis leading to higher floodwater pH was rapid in the broadcast treatment and consequently ammonia volatilization was also high (18 kg N ha^{-1}, or 36% of the applied N). Simulated ammonia volatilisation losses declined with increasing degree of incorporation and were negligible when urea was deep-point placed. Simulated results as reported by Buresh *et al*. (1991) and Singh and Thornton (1992) reasonably agreed well with many field measurements.

Heng *et al*. (2000) used CERES-Wheat to simulate the effect of irrigation and fertilizer N rates on nitrate leaching in several countries in Asia, Africa and South America. Simulation results suggested that substantial nitrate leached beyond 120 cm depth in sandy soils of northwest India, while in silty clay loam soils of Bangladesh leaching beyond the root zone was not evident. These results are also consistent with field observations in NW India (Aulakh and Bijay-Singh, 1997).

Planting Management

CERES have also been used to investigate optimum sowing dates of wheat and transplanting dates of rice for several locations in Asia. For example, using the simulation results, Timsina *et al*. (1995) suggested that the optimum rice transplanting date for Pantnagar would be from mid-June to mid-July, while the optimum sowing date for wheat would be from late October to mid-November. Likewise, they (Timsina *et al*., 1997, 2001) predicted the optimum transplanting date for rice to be 15 May in Nepal, while the optimum sowing date for wheat to be around 15 November for several locations in Nepal and northern Bangladesh. These simulations are consistent with the conventional recommended transplanting date from early to mid-July for rice in Nepal and sowing date from early to mid-November for wheat in Nepal and Bangladesh.

Based on model simulations, other authors have also suggested optimum management practices for rice and wheat. Saseendran *et al*. (1998a,b) suggested for five sites in Kerala that under rainfed conditions if only one rice crop were to be grown per year optimum transplanting date would be around first week of July, but if two crops were to be grown, the optimum transplanting date for the first rice would be earlier, around the first week of June. Hundal and Kaur (1999) suggested that the optimum date of transplanting for Indian Punjab would be around 15 June, but rice transplanted on 1 June would perform better with 30 day old seedlings instead of older seedlings and that increasing population from 11 to 44 hills m^{-2} would decrease yields, while increasing the number of seedlings per hill from 1 to 6 would increase yields. Using CERES-Rice simulations, Boonjung (2000) identified the optimum transplanting date of a photosensitive cultivar to be the first fortnight of June for northeast Thailand, while Jintrawat (1995) developed long-term strategies related to planting dates and methods (dry-seeded, or transplanted rice), also for several locations in Thailand. Results from all these simulations in India and Thailand are largely consistent with the recommended practices in those countries.

Pest and Disease Management

Relationships between crops and their pests and weather are complex, more so because populations of pests and diseases are very dynamic. Models could be useful to understand and manage pest and disease problems and to simulate their damage effects and estimate yield loss, but there are only a few examples in the literature where pest and disease components have really been linked to crop models. One such study was by Pinnschmidt *et al.* (1990), who coupled simple stem borer population model to CERES-Rice and concluded that early control, with an insecticide with 80% 'knock-down' effect, resulted in less yield loss than late control and that the highest gross margins were obtained with three pesticide applications. Pinnschmidt *et al.* (1995) also developed an approach to link population models with CERES-Rice for leaf blast, panicle blast, sheath blight, leaf folder, stem borers and plant hoppers. Pest effects were introduced by mimicking effects at the physiological process level and the 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. Development of each disease or pest was then simulated using a generic model, derived from a paralogistic growth function. Pinnschmidt *et al.* (1990, 1995) were thus able to simulate the damage effects of single or multiple pests (defoliators, weed competitors, leaf blast and sheath blight) in northwest Philippines, northwest Thailand and south Vietnam, similar to the existing practices.

Simulation results such as above on the management of N fertilizer, planting date, cultural practices and pest and disease management could be useful for researchers and policy makers for identifying management strategies to minimise ground water and atmospheric pollution and to explore agronomic and/or pest management practices in various regions of Asia. Disappointingly, there are no reports where applications of these models have resulted in the development or adoption of revised management guidelines.

Informing Policy Making and Strategic Planning

Aiding Government Policy

On a few occasions, attempts have been made to use CERES-Rice to estimate national food production and assist government policy makers in Asia. An example of this application is in Chou and Chen (1995), where the combined use of satellite imagery, GIS and CERES-Rice has been useful for mapping potential productivity and land suitability under irrigation in Taiwan. Another is in Amien *et al.* (1996) where three models, including CERES-Rice, have been used to address a concern that rice self-sufficiency, maintained since 1984, could be threatened by climate change in Java, Indonesia. Simulations suggested that climate change could increase the incidence of drought and would reduce rice yields in East and West Java, thus assisting in planning and policy making.

Crop models have also been integrated into land-use planning systems to develop and evaluate methodologies for land use analysis and to apply them on regional scale to inform agricultural and environmental policy making. An example of such applications is demonstrated by Aggarwal *et al.* (2000b), who used CERES for rice and maize, WTGROWS (Aggarwal and Kalra, 1994) for wheat and WOFOST (van Diepen *et al.*, 1988) for other crops under a SYSNET project jointly launched by IRRI, WUR and the national programs to identify suitable crops and cropping systems for various levels of yield, water use and income goals.

Although model outputs are potentially useful to aid policy makers in planning rice cultivation under irrigation in Taiwan and for the effects of climate change on national food production in Indonesia, there is no evidence of their implementations by farmers or governments or policy makers.

Likewise, though output from the projects such as SYSNET can be potentially useful for farmers and for planners in the government and non-government sectors, there is no evidence that this information has really been used by any stakeholders in the state or national levels.

Extrapolation

Models can be used to evaluate new or promising technologies developed in one location to other sites and climates and thus can complement and/or reduce the numbers of field experiments. Timsina *et al.* (1998) determined genetic coefficients for rice (BR14 and BR11) and wheat (Kanchan and Sowgat) varieties and validated the CERES models in northern Bangladesh. They then used those coefficients to predict the long-term yield trends and extrapolate the results for low (zero N, rainfed) and high (120 kg N ha^{-1}, irrigated) input systems for two other districts in northwest and central Bangladesh using local soils and weather data. Across sites, years, water and N regimes, BR11 always out-yielded BR14 and that wheat yields across sites and years were higher in the north due to lower minimum temperatures and higher solar radiation and were least in the central district due to higher temperatures and lower solar radiation, consistent with other experimental results. It is, however, not known whether such results have influenced researchers and policy makers in planning and implementing field experiments in Bangladesh and other countries in Asia.

Prediction of Greenhouse Gas Emissions

There have been very few applications of models to predict greenhouse gas (GHG) emissions from rice and wheat in Asia. Mathews *et al.* (2000a) developed the MERES model and used it to predict methane emissions from rice under a range of locations, soils, climates and management, first at the local level and then upscaled to estimate annual emissions using spatial soils data and rice growing statistics for China, India, Indonesia, Philippines and Thailand (Mathews *et al.*, 2000b). Matthews and Stephens (2002) concluded that application of the MERES model contributed mainly four benefits to the countries studied: (1) generation of baseline data for national inventories of GHG and exploring mitigation options, (2) demonstration that rice production does not exert a major force on the greenhouse effect at the global scale, although it may be a major component to national GHG budgets of some Asian countries, (3) identification of strategies for reducing methane emissions (for example, intermittent drainage in irrigated systems and improved crop residue management such as composting, mulching and early incorporation and direct seeding of rice), (4) demonstration that use of chemical fertilizer in rice entails low methane emissions, counterbalancing emissions from production and application and (5) demonstration that emissions from low-yielding rice ecosystems (i.e., rainfed, upland and flood-prone) don't justify mitigation, while irrigated rice with high baseline emissions offer win/win options for reducing emissions and maintaining yield.

MERES does not have processes to simulate 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. Methane and N_2O emissions are likely to be more significant in rice and wheat production and especially under RW systems. Methane emission dominates under continuously-flooded rice while N_2O emissions under non-flooded rice and wheat systems (Pathak *et al.* 2002, 2003b).

Impacts of Climate Change

Crop simulation models have been widely used around the world to assess the impacts of global climate change on yield and water use requirement and to identify potential adaptation strategies (Rosenzweig and Iglesias, 1994, 1998). Bachelet *et al.* (1993) and Bachelet and Gray (1993) reviewed

Table 2: Effect of climate change on simulated crop duration, yield and ET of rice in various countries in Asia

Country	No. of locations (cultivar)	Scenarios CO$_2$ level (ppm)	Temp. (°C)	RF (mm)/MR	Duration (d)	Yield (t ha^{-1})	ET (mm)	Source
Bangladesh	2 (BR)	330	0		146	6.94		Karim
		330	2		137	5.95		*et al.* (1994)
		330	4		135	5.17		
		555	0		147	8.20		
		555	2		138	7.31		
		555	4		136	6.51		
India	1 (Not	330	0		242	7.56		Hundal and Kaur
	specified)	330	1.5		244	6.90		(1996)
		330	3		247	7.18		
		600	0		247	6.78		
		330	1		242	7.14		
		330	2		244	7.00		
		600	1		242	7.64		
		600	2		244	7.34		
India	4 (PR106)	330	0			7.30	660	Lal *et al.* (1998)
		600	0			9.00	645	
		900	0			10.80	640	
		330	-4			5.70		
		330	-2			6.60		
		330	0			6.20		
		330	2			4.50		
		330	4			3.60		
		750	-4			6.50		
		750	-2			7.80		
		750	0			7.00		
		750	2			5.90		
		750	4			4.80		
		330	0	WW1		6.00		
		330	0	WW2		5.50		
				WW3		3.80		
		750		WW1		7.40		
		750		WW2		7.00		
		750		WW3		5.00		
India	5 (Jaya)	330	0			3.95	550	Saseendra *et al.*
		630	0			4.30	520	(2000)
		930	0			4.50	503	
		460	-4			4.75		
		460	-2			4.50		
		460	0			3.95		
		460	2			3.40		
		460	4			2.60		
		460	-4	-15		1.95		
		460	-2	-5		2.95		
		460	0	0		3.98		
		460	2	5		4.40		
		460	4	15		5.35		
Japan	3	330	0		120-143	5.30		Seino (1995)
		330	2		111-122	4.50		
		330	4		105-111	3.80		
		330	0	-20	120-143	5.30		
		330	0	20	120-143	5.30		
		555	0		120-143	4.0		
Thailand	4	330	0		107	4.71	596	Tongyai (1994)
		330	2		101	3.53	592	
		330	4		102	2.57	606	

Table 2: Contined

	555	0	107	6.18	586	
	555	2	101	5.17	588	
	555	4	102	4.07	612	
1	330	0	103	9.00		
Philippines	330	0	104	9.00		Singh and Padilla
	330	2	96	8.30		(1995)
		4	92	6.50		
	660	0		10.50		
		2		9.50		
		4		8.00		
Philippines 2	330	0		7.80		Singh and Ritchie
	330	2		6.50		(1993)
	330	4		4.00		
	540	0		8.70		
	540	2		7.50		
	540	4		4.80		
Philippines 2	330	0		4.98		Escano and
	330	2		3.98		Buendia (1994)
	330	4		3.12		
	555	0		6.12		
	555	2		5.18		
	555	4		4.30		

*Crop duration, yield and ET are, respectively in days, t ha^{-1} and mm, RF and MR denote rainfall (mm) and moisture regime, respectively, WW1, WW2, WW3 denote current water management and moderate and high water conservation scenarios, respectively

three rice models (MACROS, CERES-Rice and RICESYS) to evaluate their suitability for assessing the impact of climate change in the Philippines. Grain yield response of MACROS and CERES to temperature and CO_2 and yield response of RICESYS to temperature, agreed well with the glasshouse experimental data (Baker *et al*., 1990a,b). CERES-Rice predicted a lower impact of temperature change on potential rice yield than MACROS, but 15% increase in potential yield due to doubling of CO_2 concentration compared with 9% by MACROS, consistent with observations by Baker *et al*. (1990b).

CERES rice and wheat have been used in several studies to study the effect of climate change on rice and wheat production in Asia (Table 2-5). In all those studies, climate change scenarios were generated either by changing daily local weather parameters (temperature, radiation, rainfall) and global CO_2 concentration singly or in combination, or by the General Circulation Models (GCMs) of which the four were most commonly used - Goddard Institute for Space Studies (GISS) (Hansen *et al*., 1983), Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald, 1987), United Kingdom Meterological Office (UKMO) (Mitchell *et al*., 1989) and Canadian Climate Centre (CCC) (Wilson and Mitchell, 1987). The difference between $1\times CO_2$ (current climate) and $2\times CO_2$ (current climate with a doubling of CO_2) mean monthly temperatures, $2\times CO_2{:}1\times CO_2$ and monthly precipitation totals were determined using the GCMs. The historical daily weather data for use in the crop models under climate change were then adjusted based on the changes in the monthly means generated by the GCMs.

Rice

CERES-Rice has been used to study the impact of climate change and CO_2 enrichment on phenology, growth, yield, ET and irrigation requirement of rice in Bangladesh (Karim *et al*., 1994), China (Zhiqing *et al*., 1994, 1995), Indonesia (Parry *et al*.,1992; Amien *et al*., 1996, 1999), India (Hundal and Kaur, 1996; Hundal *et al*., 1998; Lal *et al*., 1998; Saseendran *et al*., 2000; Aggarwal and Mall, 2002), Japan (Seino, 1994, 1995), Malaysia (Parry *et al*., 1992), Nepal (Timsina *et al*., 1997), Philippines (Singh and Ritchie, 1993; Escano and Buendia, 1994; Singh and Padilla, 1995;

Table 3: Effect of GCM scenarios on changes in simulated crop duration (increase or decrease by days from base climate) and in simulated yield, irrigation requirement and ET of rice (% change from base climate) in various countries in Asia

Country	No. of locations (cultivar)	Scenarios CO_2 level (ppm)	GCM	Moisture regime	Duration*	Yield*	Irrigation requirement*	ET*	Source
Bangladesh	2(BR3, BR11)	330	GISS	Irrigated		-11 to -22			Karim *et al.* (1994)
			GFDL			-14 to -27			
			UKMO			-19 to -25			
		555	GISS		-11 to 1	0 to 8			
			GFDL		-13 to 1	5 to -6			
			UKMO		-14 to 1	2 to -6			
China	9 (various)	330	GISS	Rainfed		-10 to -78			Zhiqing *et al.* (1995)
			GFDL			-6 to -33			
			UKMO			-8 to -35			
		555	GISS			5 to -72	603 to -27	15 to -27	
			GFDL			27 to -13	53 to -63	0 to -10	
			UKMO			21 to -12	69 to -42	25 to -7	
		330	GISS	Irrigated	-7 to -22	-15 to -33			
			GFDL		-11 to -21	-14 to -37			
			UKMO		-12 to -26	-19 to -31			
		555	GISS		-5 to -20	6 to -12		0 to 25	
			GFDL		-10 to -20	3 to -15		4 to -18	
			UKMO		-10 to -26	3 to -9		16 to - 8	
Japan	3 (not specified)	330	Base	Irrigated	103 to 286	2.53 to 3.81	-	-	Seino (1995)
		555	GISS		-15 to -26	6 to -12	15 to 44	9 to -1	
			GFDL		-15 to -31	0.2 to -11.3	4 to 13	-2 to -10	
			UKMO		-17 to -35	2.5 to 6.4	10.1 to 44	0.2 to 9.1	
Philippines	2 (IR 64)	330	Base		121	4.03 to 5.92	928 to 1659	421 to 586	Escano and Buendia (1994)
		330	GISS		-8	-38	-10	3	
			GFDL		-6	-27	21	3	
			UKMO		-8	-29	-8	-26	
		555	GISS			-39			
			GFDL			30			
			UKMO			30			
	6 (IR64, IR72)	555	GISS			10 to -85			Buan *et al.* (1996)
			GFDL			23 to -3			
			UKMO			17 to -22			
			CCCM			13 to -7			
Thailand	4 (RD 23)	330	Base	Rainfed		1.8 to 3.5			Tongyai (1994)
		330	GISS			-34 to -44			
			GFDL			-11 to -20			
			UKMO			-25 to -48			
		555	GISS			-6 to -16			
			GFDL			11 to 25			
			UKMO			-23 to 10			
		330	Base	Irrigated		4.4 to 5.1			
			GISS			-29 to -44			
			GFDL			-12 to -31			
			UKMO			-28 to -48			
		555	GISS			-2 to -12			
			GFDL			-2 to 12			
			UKMO			-18 to -1			

*Crop duration and yield for base runs are respectively in days and t ha^{-1} and irrigation requirement and ET are in mm

Buan *et al*., 1996) and Thailand (Parry *et al*., 1992; Tongyai, 1994) (Table 2 and 3). In most of those studies, increase in temperature by 2-4°C reduced simulated growth duration and yield, with larger decreases for lower and smaller decreases for mid- to high-latitudes (Table 2). For example, in Japan with mid-latitudes (Seino, 1994, 1995), temperature increases of 2 to 4°C reduced growth duration of rice by 9 to 32 days and yield by 9 to 32% and changed ET by -2 to 6 mm. Increased temperatures by 4°C increased the irrigation water requirement by 7-38% with 330 ppm CO_2, but the water requirement decreased by 3-9% for no temperature increase and for CO_2 increase to 555 ppm (data not shown). In all three studies in the Philippines with low latitudes, increased temperatures by 4°C due to climate change decreased yield by 20-50%. In the study by Singh and Ritchie (1993), increased temperature by 4°C reduced water-use efficiency but increased N mineralization rate from 0.29 to 0.33 kg ha^{-1} day^{-1} with zero N and from 0.35 to 0.42 kg ha^{-1} day^{-1} with 120 kg N ha^{-1}. In China, increased temperatures by 4°C would increase the area for rice cultivation as the northern limits for double rice and triple rice systems could be moved northward by about 5-10° of latitude (Zhiqing *et al*., 1994, 1995). For Malaysia, Parry *et al*. (1992) concluded that rice yields might decline by 12-22% and the demand for rice irrigation would increase by about 15%. Various climate scenarios generated by the three GCMs predicted variable effects on growth, yield, ET and irrigation requirement of rice (Table 3), suggesting the need for thorough re-evaluation of the GCMs for climate change studies.

Most studies suggest that under the current temperature regime, rice yields would increase with increase of CO_2 from current (330 μmol mol^{-1}) to high (≥ 660 μmol mol^{-1}) concentrations. Singh and Padilla (1995) suggested that increased CO_2 concentrations would reduce transpiration and N losses and increase water-, N- and radiation-use efficiencies. Karim *et al*. (1994) 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 would decrease and the country's food security for the increasing population would be threatened. Zhiqing *et al*. (1994, 1995) showed that in China the direct effects of increased CO_2 concentration would compensate for the negative effects of increased temperature on rainfed rice at most sites, except where rainfall would sharply decrease due to climate change. With irrigation, rice yields in China would increase at higher CO_2 concentrations compared with the baseline yields in the northern sites but would decrease in the central and southern sites.

Climate change could increase or decrease rainfall in conjunction with increase or decrease of solar radiation and temperatures. Amien *et al*. (1996, 1999) reported that doubling greenhouse gases would increase minimum and maximum temperatures and increase the solar radiation by 1.2-2.1% and rainfall by 20.5-91.7% in Indonesia. In rainfed areas of both India and Indonesia, any decrease in rainfall due to climate change would decrease rainfed rice yields, while increased rainfall would increase yields (Amien *et al*., 1996, 1999; Saseendran *et al*., 2000). In the tropical areas of Kerala, there would be an exponential increase in simulated rainfed rice yield for an increase in rainfall by up to 15 mm day^{-1} above the local rainfall, but a yield loss of about 50% for a decrease in rainfall by 15 mm day^{-1} (Saseendran *et al*., 2000). In China, the amount of water needed for irrigation would increase greatly in areas where rainfall decreased sharply and ET of rainfed rice would usually be less than that for irrigated rice, suggesting that rainfed upland rice could be developed in areas where irrigation water is not available (Zhiqing *et al*., 1994, 1995). Increased rainfall would increase the chance of flooding in tropical and sub-tropical regions with monsoonal climates, such as parts of the Philippines, where simulated rainfed rice yields were decreased by 10% increase in rainfall, due to flooding in the areas with already high seasonal rainfall and for similar rainfall regime in Indonesia, yields did not reduce with about 10% decrease in seasonal rainfall (Buan *et al*., 1996). In Japan, while increased precipitation reduced irrigation requirement, decreased precipitation did not have any adverse effect on the simulated yield of irrigated rice (Seino, 1994, 1995).

CERES has also been used to study the effect of climate change on disease development. For example, CERES-Rice, coupled with BLASTSIM (Luo *et al*., 1995, 1998), was used to study the

Table 4: Effect of climate change on simulated yield (t ha^{-1}) and ET (mm) of wheat in various countries in Asia

Country	No. of locations (cultivar)	Scenarios CO$_2$ level (ppm)	Temp. (°C)	Rainfall (mm)	Yield (t ha^{-1})	ET (mm)*	Source
India	2 (Kalyansona)	330	0		1.80		Rao and Sinha (1994)
		330	2		1.20		
		330	4		0.80		
		555	0		2.70		
		555	2		1.85		
		555	4		1.20		
		330	0	+20%	2.0		
		330	2		1.30		
		330	4		0.85		
		555	0	+20%	3.10		
		555	2		2.00		
		555	4		1.32		
		330	0	-20%	1.85		
		330	2		1.77		
		330	4		0.90		
		555	0	-20%	2.74		
		555	2		1.95		
		555	4		1.37		
India	4 (HD 2285)	330	0		6.30	350	Lal *et al.* (1998)
		600	0		8.60	320	
		900	0		10.40	280	
		330	-4		5.70		
			-2		6.30		
			0		6.00		
			2		4.60		
			4		2.70		
		750	-4		6.80		
			-2		7.50		
			0		7.80		
			2		6.80		
			4		5.00		
		330	0	WW1	6.10		
		330	0	WW2	6.00		
				WW3	5.60		
		750		WW1	7.60		
		750		WW2	7.70		
		750		WW3	7.70		
Japan	3 (not specified)	330	0		2.53		Seino, 1995*
		330	2		2.30	-2 to -5%	
		330	4		2.00	-2 to -9%	
		330	0	-20	2.35	-3 to -7%	
		330	0	20	2.56	1 to 5%	
		555	0		2.3	-6 to -9%	
Pakistan	4 (Mexipak)	330	0		4.59		Qureshi and Iglesias (1994)
			2		3.80		
			4		3.09		
		555	0		5.65		
			2		4.80		
			4		3.95		

*ET values for Japan are increase or decrease (%) from base runs, WW1, WW2 and WW3 for India represent normal irrigation and moderate and high water conservation, respectively

effects of global climate change on leaf blast epidemics and consequent yield losses in several countries in Asia. Simulations over a 30 year period for 53 locations in Philippines, Thailand, China, Japan and Korea suggested that climate change would have a significant effect on disease development which

Table 5: Effect of GCM scenarios on changes in simulated crop duration (increase or decrease in days from base runs) and in simulated yield, irrigation requirement and ET of wheat (% change from base climate) in various countries in Asia

Country	No. of locations (cultivar)	Scenarios CO2 level (ppm)	GCM	Moisture regime	Duration*	Yield*	Irrigation requirement	ET	Source
Japan*	3 (not specified)	330	Base		192 to 286	2.53 to 3.81	-		Seino (1995)
		555	GISS		-12 to -21	6 to -9		2.1 to -10.1	
			GFDL		-10 to -21	-8 to -20		-3.1 to -11.4	
			UKMO		-10 to -33	-19 to -41		0 to -23.1	
Pakistan*	4 (Mexipak)	330	Base	Rainfed	128 to 150	0.6 to 4.98	-		Qureshi and Iglesias (1994)
		330	GISS			16 to -67	-	-5 to -41	
			GFDL			8 to -55		1 to -36	
			UKMO			-11 to -80		-5 to -50	
		555	GISS			67 to -41		-5 to -35	
			GFDL			50 to -45		2 to -33	
			UKMO			29 to -61		-4 to -44	
		330	Base	Irrigated	125 to 150	3.73 to 5.28	-	-	
			GISS		-12 to 22	-17 to -60	-8 to -45	-17 to -31	
			GFDL		-13 to -21	33 to -54	57 to -43	25 to -29	
			UKMO		-11 to -26	-12 to -74	33 to -56	13 to -42	
		555	GISS			-2 to -36	-16 to -43	-23 to -32	
			GFDL			60 to -37	43 to -33	18 to -31	
			UKMO			6 to -56	20 to -47	3 to -38	
India	2 (Kalyansona)	330	Base	Rainfed	125	1.80	-	-	Rao and Sinha (1994)
		330	GISS		-8 to -10	-27 to -58		-8	
			GFDL		-3 to -9	-11 to -39		-13	
			UKMO		-14 to -15	-56 to -66		-22	
		555	GISS			6 to -27			
			GFDL			31 to -11			
			UKMO			-35 to -44			
		330	Base	Irrigated	128	4.51	-	-	
		330	GISS		-10 to -20	-53 to -61		-26	
			GFDL		-3 to -18	-17 to -40		-20	
			UKMO		-14 to -26	-64 to -67		-33	
		555	GISS			-32 to -34			
			GFDL			-20 to 22			

*Crop duration and yield for base runs are respectively in days and t ha^{-1}

would vary according to agroecological zone. In cool subtropical or temperate zones, such as northern 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.

Wheat

CERES-Wheat has also been used to study the impacts of climate change on wheat production in India (Rao and Sinha, 1994; Hundal and Kaur, 1996; Lal *et al*., 1998), Japan (Seino (1994,1995), Nepal (Timsina *et al*., 1997) and Pakistan (Qureshi and Iglesias, 1994) (Table 4 and 5). In all those studies, increased CO_2 concentrations and decreased temperatures increased growth duration and yield, while increased temperature shortened growth duration and reduced leaf area, biomass and yield (Table 4). For example, in Pakistan, an increase in temperature by 4°C would reduce growth duration and decrease yield dramatically under both dryland and irrigated conditions. The study further suggested that Pakistan could be one of the countries in Asia most severely affected by climate change with country's wheat production decreasing substantially (Qureshi and Iglesias, 1994). The yield decreases due to increased temperature by 4°C would however be partly countered by the positive physiological effects of increased CO_2 from 330 to 555 ppm. In northern Japan, an increase in temperature by 4°C reduced growth duration by up to 30%, ET by up to 9% and yield by up to 30%, but in south-western Japan, they were, respectively reduced by only 10-20%, 3-4% and 7-15%. While increased CO_2 concentration compensated for the effect of increased temperature in central and northern Japan, it did not do so in southern Japan (Seino, 1994, 1995). In the western districts of Nepal, simulated wheat yields increased with increasing CO_2 concentration from 330 to 660 ppm and by increasing temperature (1-2°C) in the temperate hills but decreased in the sub-tropical plains (K. Sherchand, National Agricultural Research Council, personal communication). As for rice, various climate scenarios generated by the three GCMs predicted variable effects on growth, yield, ET and irrigation requirement of wheat (Table 5), again suggesting the need for thorough re-evaluation of the GCMs for climate change studies.

Iglesias *et al*. (1996) concluded that of the two crops, the production of rice generally did not benefit from overall climate change. Rosenzweig *et al*. (1993) provided the detailed analyses of the causes of increase or decrease in yield under the various climate change scenarios in low-, mid- and high-latitude areas. Under the climate change scenarios reviewed and assessed, the effects on crop yields in mid- and high-latitude regions appeared to be less adverse than those in low-latitude regions. At low latitudes, crops currently grown at higher temperatures result in accelerated growing periods, more severe heat and water stress and produce low yields. In mid- and high-latitude areas, where current temperature regimes are cooler, increased temperatures, while still shortening grain-filling periods, thus exerting a negative influence on yields, do not significantly increase stress levels. At some sites near the high-latitude boundaries of current rice and wheat production, increased temperatures can benefit crops limited by cold temperatures and short growing seasons. Simulated yield increases in the mid- and high-latitudes thus are caused primarily by (i) positive physiological effects of CO_2, i.e., increased photosynthesis can more than compensate for the shortening of the growing period caused by warming (ii) lengthening of growing season and amelioration of cold temperature effects on growth, i.e., increased temperatures can extend the frost-free growing season and provide regimes more conducive to greater crop productivity. The primary causes of decreases in simulated yields in low-latitude areas are: (i) shortening the growing period, especially the grain-filling stage, due to high temperatures (ii) decrease in water availability due to combination of factors such as increases in ET rates, enhanced losses of soil moisture and, in some cases, a projected decrease in rainfall (iii) poor vernalization in winter wheat.

Adaptation Measures

In all the climate change studies, increased temperature had more adverse effects on simulated yields of wheat than of rice. Further, the positive effects of increased CO_2 concentration in both crops were offset, to varying extents, by the negative effects of higher temperatures and decreased rainfall. Based on the simulation results from various countries, Rosenzweig *et al*. (1993) and Rosenzweig and Iglesias (1994, 1998) highlighted and discussed two farm-level adaptations to future climate change. Adaptation level 1 implies little change to existing agricultural systems, reflecting relatively easy farmer response to a changing climate and included shifts in planting date by +/-1 month, additional applications of irrigation water and changes in crop variety more adapted to altered climate. Adaptation level 2, on the other hand, implies more substantial change to agricultural systems, possibly requiring resources beyond the farmer's means and included large shifts in planting date (> 1 month), increased fertilizer application, installation of irrigation systems and development of new varieties. Simulation results indicated increases in rice and wheat yields in various magnitudes in different countries if those adaptive measures were followed under the changed climate. For example, with earlier planting, increased temperature increased simulated rice and wheat yields in northern Japan, but not in southern Japan (Seino, 1994, 1995). In India, increased N fertilizer and plant population slightly reduced the negative impacts of climate change on the simulated wheat yield (Rao and Sinha, 1994). In China, adaptive measures included intensive management and the possibility of a tripartite structure of planting that would entail coordinated development of grain, feed and cash crops (Erda, 1996). 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.

The literature reveals a large numbers of studies on the effect of climate change on rice and wheat productivity in Asia, which have undoubtedly gained the widespread acceptance within the research community. The outputs from those studies do provide useful information that could potentially support decisions on cropping strategies. However, unfortunately, there has been no mention as to whether the results have been used in policy consideration or whether they are merely of scientific or research interest.

Conclusions and Future Research Needs

The literature review reveals that CERES rice and wheat have been extensively used for various applications in Asia. Major applications include yield gap and yield trend analyses, evaluating agronomic management strategies, evaluating cropping options in new locations, predicting greenhouse gas emissions, pest and disease management, informing government policy makers for planning and climate change impacts and adaptations. Of all the reported applications, the models have been used most extensively for predicting the effects of climate change (temperature, radiation, rain) on crop yields, with effects varying with countries and locations. Most studies reveal that the simulated yields of both crops were frequently reduced by increased temperature due to reduced growth duration, though increased temperature could also expand the geographically suitable regions, such as shifting the boundary for rice production in China further North. While increasing temperature generally reduced both simulated rice and wheat yields, this was often partially or fully compensated for by increasing CO_2 concentration. The results suggest that some of the biggest impacts of climate change would be reduced wheat yields in Pakistan and Northwest India, reduced rice yields in Bangladesh, Malaysia and Thailand and variable effects depending on latitude in China and Japan. The impacts would vary from largely positive to largely negative based on the uncertainty in the climate change scenarios predicted by GCMs. The results further suggest that climate change could have huge impacts on local and regional food security, however the negative climatic change impacts on yield could be reduced to varying degrees by adapting strategies such as changing planting dates, increasing fertilizer and irrigation amounts and use of more heat tolerant cultivars.

There are current and potential future uses of CERES for improving research understanding and crop management decisions, in policy planning and implementation and in preparing for future climate change. Although the CERES models have been extensively used by scientists to identify optimum crop, nitrogen and pest management strategies that could be useful for policy makers for identifying and implementing management strategies, disappointingly there is no evidence showing the applications of these models in the development or adoption of revised management guidelines in Asia. Further, despite a great deal of model use by the scientific community, frustratingly there is no evidence to date of use or uptake of the model outputs by farmers, governments, or other clients and stakeholders. The research on climate change since the late 80s has created vast interest within scientific or research community as well as within the policy makers. Various studies on the impacts and adaptation of climate change showed that the model results could be potentially useful to farmers and would aid policy makers in preparing and planning for a future changed climate and for meeting the food demands of farmers and for local, regional and national levels. There has, however, been very little, or perhaps no, evidence that such information has really been used by any stakeholders or policy makers in the state or national levels in the countries of Asia.

Nevertheless, along with the considerable current and future potential applications, there may also be misrepresentation, misuse and misunderstanding of these tools. As for most models, there are potential limitations of CERES rice and wheat that must be clearly understood before attempting them to apply for the intended use. Many times, the models contain many simple, empirically-derived relationships that do not completely mimic actual plant processes. Such relationships may or may not hold under differing climatic conditions, particularly under the higher temperatures predicted for doubled CO_2 with global warming. Other simplifications and assumptions are that weeds, diseases and insect pests are fully controlled and that problem soils such as salinity, acidity, or sodicity do not exist. Further, models do not respond to catastrophic events such as heavy storms and typhoons or cyclones that can cause severe lodging and complete damage to crops.

The adaptation simulations for reducing the adverse impacts of climate change reviewed were not comprehensive because all possible combinations of farmer responses were not tested at every site where climate change studies were carried out. Spatial analyses of crop, climatic and soil resources are needed to test fully the possibilities for crop substitution. Further, neither the availability of water supplies for irrigation nor the costs of adaptations, the critical needs for research, were considered in those studies. Future research needs on climate change include determining how countries, particularly the developing ones, can and will respond to reduced yields under a changed climate and detailed adaptation studies in various countries will help address this need. Another important need is that in order to minimize possible adverse consequences of climate change, the agricultural sector should be encouraged to continue to develop crop breeding and management programs for heat and drought conditions. Irrigation infrastructure should require improvement but possible adverse effects of secondary salinity arising from irrigation should also not be underestimated. Thus, while adaptation level 1 will require minimum support to farmers to adpat to changed climate, the adaptation level 2 may require substantial changes in currrent agricultural systems, investment in regional and national agricultural infrastructure and policy changes.

By recognizing the many simplified processes, assumptions and guesses made during the development of these models, we conclude that, there is a continuing need for the inclusion or modification of the robust scientific processes and the inclusion of more coefficients and parameters based on scientific research and field experimental data. These models, intended for research, crop management and policy applications, should be evaluated widely in diverse field environments where rice and wheat are grown. One of the major limitations for the scientific community is the unavailability of quality input data on weather, soil and crop management for model evaluation. Overall review results however, suggest that while these models have been applied extensively in rice and wheat growing areas of Asia, they need rigorous evaluations for a range of variables and key bio-physical processes against a range of data sets from those areas as emphasized in Timsina and Humphreys (2006). Lastly, while recognising both the potential limitations and strengths of the model results, efforts should be continued to facilitate the uptake of model results by farmers, stakeholders and the policy makers in Asia if CERES rice and wheat have to make contributions in the real world.

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