Applications of systems simulation for understanding and increasing yield potential of wheat and rice

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Applications of systems simulation for understanding and increasing yield potential of wheat and rice

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Propositions

1. At the level of N management currently practiced by (IRRI) breeders, the search for higher yield potential may be impossible even though the germplasm being screened may possess appropriate traits.
   This Thesis

2. Decision-making processes based on field experiments often have uncertainties due to inadequate understanding and lack of appropriate data that may be overcome by the application of systems approaches.
   This Thesis

3. Growing period based agro-ecological zoning in the tropics is appropriate only when agriculture is based on monoculture cropping and rainfall is the principal variable determining crop yield such as in large tracts of semi-arid regions.
   This Thesis

4. To determine the optimal duration of wheat, a breeding program based on few years of experimentation must be supported by growth simulation for a large number of years to account for the climatic variability.
   This Thesis

5. The perceived widespread yield decline in productivity of intensive cropping systems in Indo-Gangetic plains is a myth.

6. The current policy to subsidize the costs of fertilizers, water and energy, driven by short-term socio-economic and political concerns, may lead to a long-term sustainability problem.

7. Greater agricultural intensification in combination with diversification is the key to prevent social, political, ecological and economical disasters in most developing countries.

8. Winners do not do different things, they do things differently.
   Shiv Khera

9. Environmental issues are exaggerated by a select group of scientists to sustain their research interests.

10. In today's world, values are perceived by many as disposable if the price is right.

Propositions associated with the Ph.D. Thesis of Pramod K. Aggarwal:
Applications of systems simulation for understanding and increasing yield potential of wheat and rice.

Wageningen, April 17, 2000

Abstract

Understanding and increasing yield potential of cereals is essential to meet the growing food demand in Asia. A crop growth simulation model -WTGROWS- was developed to quantify the climatically determined potential grain yields and yield gaps in wheat in tropics and sub-tropics. The model written in PCSMP simulates daily dry matter production as a function of solar radiation, maximum and minimum temperatures, and water and nitrogen stresses. Comparison of simulated and measured quantities indicated satisfactory performance of the model in reference to water and nitrogen uptake, dry matter growth and grain yield in potential as well as water- and N-limited environments. The wheat yield potential in India varied between 2.6 and 8.3 t ha^{-1} depending upon the location. Economically optimal yields in irrigated environments were estimated for all locations based on current price ratios of N fertilizer and grain, native soil fertility, simulated crop response to N fertilizer and other costs related to transport, harvesting and market forces. Yield gaps were found to be small in irrigated regions of northwestern India but significantly large in eastern regions. Almost 35 - 50% of the gap could be ascribed to delayed sowing. Crop simulation with different amounts of nitrogen and irrigation showed significant interaction between water and N availability and climatic variability, particularly with low inputs. The effect of climate change was more pronounced in central India where yield potential is already low.

The model was also used to explore the opportunities for growing wheat in irrigated and rainfed tropical southeastern Asia. The results indicated that potential yields exceed 3 t ha^{-1} at all places and increased further with latitude and elevation. At sea level, between equator and 8°N latitude, potential grain yield was 3 t ha^{-1}. It increased to 5 t ha^{-1}at 21°N and 4.5 t ha^{-1}at 10°S latitudes. Realization of the yield potential of the presently available varieties may be limited because of several agronomic constraints.

A simulation framework has been developed to determine the relative importance of different plant traits in isolation or in combination for increasing yield potential. In this approach, hypothetical genotypes are 'created' by changing the specific crop parameters of a crop simulation model. The impact of simultaneous change in many traits is assessed by randomly combining different traits in the hypothetical genotype. The approach is illustrated with examples for rice in tropics. No trait individually or in combination provides more than 5% advantage in yield at the level of management typically practiced by breeders. In such environments, even though genotypes may possess traits for higher yield potential, they will not be able to express them. Another framework is presented for using crop simulation models and statistical analysis together to increase the efficiency of multi-environment genotype testing.

Key words: modelling, yield potential, yield gap, ideotype, genotype by environment interaction, breeding, systems approach, wheat, rice

Preface

Understanding yield potential of food crops in different agro-environments and strategies for increasing this has been a major focus of agricultural research in most developing and populous countries such as India. This has also been the topic of my research ever since I joined Indian Agricultural Research Institute (IARI) at New Delhi, India 24 years ago as a Crop Physiologist. Since large areas in India are rainfed or receive limited irrigation, understanding drought resistance mechanisms in wheat was my first assignment.

This research gave me the realisation that such experimental research in fields needs to be supplemented by quantitative understanding. That is when I started learning crop modelling. I went to the International Rice Research Institute (IRRI), Philippines in 1985 to do my Post-Doctoral work on sustainability and diversification of rice-based cropping systems. Frits Penning de Vries joined IRRI at about the same time. This provided me an opportunity to collaborate with him on using MACROS modules to explore opportunities for growing wheat in rice based systems of tropics of Southeast Asia. In the process, I learnt PCSMP and basics of crop simulation. Section two of the thesis is the result of this research.

After returning back to the Indian Agricultural Research Institute in 1987, I got involved in the Simulation and Systems Analysis in Rice Production (SARP) project which provided me further stimulus to focus more on systems simulation research. With the support of Frits, Hein Ten Berge, Martin Kropff and Herman Van Keulen, we were able to evolve MACROS into WTGROWS to meet our requirement of a spring wheat model for tropical and sub-tropical environments of India. Our focus subsequently shifted to applications of WTGROWS to determine the opportunities for wheat in different agro-environments of India. This research forms the bulk of section one of this thesis.

In 1994, IRRI invited me to be the Co-ordinator of the Potential Production theme of the SARP project. The emphasis of the whole project was then on applications of crop models. During my two years of stay, I was required to assist the network scientists in different countries of Asia in model development and in their case studies. My own research in this period focused on improving the ORYZA1 model and its applications in plant breeding. For this, I worked closely with Martin Kropff and several other scientists of IRRI. This research is reported in the final section of this thesis.

This assignment also provided me an opportunity to work for some time at AB-DLO, Wageningen. Here, I came in contact with Professor Rudy Rabbinge who together with Martin Kropff encouraged me to submit my simulation research as a thesis to Wageningen Agricultural University. This thesis would not have been possible without their active and persistent support and encouragement.

Several colleagues at IARI and IRRI have been associated with the research reported in this thesis. I have enjoyed working with them and would like to acknowledge their

support. Today, IARI is putting a special attention to applications of systems simulation in agriculture. I am grateful to Professors S.K. Sinha and R.B. Singh, the past and current Director of IARI for providing such an environment and for their consistent financial, technical and administrative support for my research. Finally, I would like to acknowledge the help provided by Gon van Laar in setting the layout of the thesis and other editorial matters.

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Contents

1. General introduction

Wheat and rice are the two most important staple food crops for a large majority of the world's population. At several places, in particular in south Asia, yield and production of both crops has increased considerably during the last three decades. In case of India, for example, the production of wheat has increased from 12.3 Mt in 1965 to 70 Mt in 1999 and the mean productivity has increased from 0.99 t ha^{-1} to 3.1 t ha^{-1}, respectively. The later was largely due to the development and large-scale cultivation of new higher yielding semi-dwarf varieties in the early sixties and greater applications of water, nutrients and pesticides. Such transformation was more apparent where agricultural infrastructure was in place such as in north-western India and central Luzon of Philippines, and support of government policy was available.

These increases in cereal production made most of the Asian region self sufficient and contributed tremendously to their food security. The later, however, is now at risk due to the continuously increasing population. The world population has more than doubled since 1950. This increase has been predominantly in the less developed regions of the world, in particular in Asia. South Asia, comprising the Indian subcontinent is home for almost one quarter of the world population. It is projected that about 3.8 billion more people will be added to the world's population by 2050. Most of this increase will be in the developing countries. An additional population of about 700 million people, approximately equal to the current population of Europe will be added in the South Asian region alone in next 30 years assuming a medium growth rate. By 2050, India's population is expected to grow to 1.6 billion people and will outgrow China as the most populous country of the world (UN, 1997).

This rapid and continuing increase in population implies a greater demand for food. Although the world as a whole may still have sufficient food for everyone, it would need to be produced where needed due to socio-economic and political compulsions (Rabbinge, 1999). The food will have to be produced from the same or even shrinking land resource because in most Asian countries, in particular in southern Asia, there is no additional land available for cultivation. It is believed that in the 21st century, the world food situation will be largely influenced by the changes that occur in Asia (Rabbinge, 1999). There is also likely to be a significant shift in the type of food needed in the future. It is projected that 51% of the Asian population will be living in the urban areas in 2020 as compared to 32% at present (UN, 1997). Historical evidence has shown that the demand for cereals is generally reduced with urbanization. Yet, in absolute terms, the demand for wheat and rice will be very high. It is estimated that the demand for total cereals in Asia will increase to 10430 million tons by 2020 from a benchmark demand of 695 million tons in 1993 (IFPRI, 1995). The Asian rice production alone must increase to more than 800 million tons over the next 30 years from the present level of about 500 million tons (Hossain, 1995).

Although there is now large pressure to increase production, there has lately been a significant slow down of the growth rate in area, production as well as yield. The rate of annual growth of food production and yield showed a peak during early years of green revolution but since then there has been a decline in its growth rate. Increase in area under cultivation does not look feasible. However, due to increasing population, food production per person has become constant during 1980s. Continuously increasing population pressure, urbanization and income growth could further lower the availability unless corrective measures are taken (Pinstrup Anderson and Pandya-Lorch, 1995). Further production increase has to come, therefore, from an increase in productivity per unit area. These estimates further indicate that by 2025 irrigated rice yield must increase from the current 5 t ha^{-1} to 9.3 t ha^{-1} in Asia if rainfed yields do not change. The rice yield in the irrigated ecosystem should be 8 t ha^{-1} even if the yield in rainfed ecosystems can be increased to 4 t ha^{-1}.

What adds to the worry of food planners, is that grain yields in experimental farms are also stagnating and the deteriorating soil health of intensive cropping regions. The yield potential of rice in tropics has not increased above 10 t ha^{-1} since IR8 was released 30 years ago, despite significant achievements in attaining yield stability, increasing per day productivity and improving grain quality (Aggarwal et al., 1997). The yield of major cereals in north-western India has also not shown any significant increase during last few decades (Sinha, 1999). The gradual increase of environmental degradation is compounding the problem, early signs of which are becoming visible in areas that benefited largely from the green revolution technologies. There is now a great concern about decline in soil fertility change in water table, rising salinity, resistance to many pesticides and degradation of irrigation water quality, for example in north-western India (Sinha et al., 1998).

Thus, there is a tremendous challenge facing agricultural scientists to develop technologies for a larger food production in the coming decades. There is an urgent need to secure the past yield gains and further increase the yield potential of major food crops. It is very important to know how much additional cereals, particularly the staple food crops rice and wheat, can be produced by different regions of Asia to meet the increasing demand. In case of population rich and low income regions of Asia, it is also important to know where and at what cost this can be produced with current technology and what alternative technologies will be needed to meet the desired production targets. The future increases have to be achieved from less land with less inputs such as labour, water, nitrogen and pesticides in such a way that the scarce natural resources remain conserved.

The potential of a crop to produce is determined by the interactions of the climatic conditions of a region with its soil and crop characteristics. Crop growth simulation models are ideal tools to determine its value in different agro-climatic regions and also to quantify the magnitude of yields gaps and their principal causes. A large number of crop models have been developed during the last three decades. Models are now available for all major crops such as wheat, rice, maize, sorghum, millet, chickpea, pigeonpea, groundnut, sunflower, sugarcane, potato and even for plantation and horticultural crops. Together with Geographical Information Systems (GIS), databases, optimization techniques and other tools of systems research, these models present a new opportunity for assessing potential production in a region, facilitate analysis of the sustainability options for agricultural development including planning of resource allocation.

Several studies for determining production potential of a field, farm or region have been conducted in the recent past using systems simulation. At the field level, there are enormous examples from different regions of the world and with different crops where crop growth models have been employed to study the genotypic potential of existing or alternate genotypes, traits that maximize yield potential, management strategies needed to attain specified yield level and magnitude of yield gaps and supplementing experimental results with simulated yield estimates (Muchow et al., 1990; Boote and Tollenaar, 1994; Kropff et al., 1994; Hammer et al., 1996; Dingkuhn and Sow, 1997; Kropff et al., 1997). At the farm level, crop growth models have often been combined with household economy models to optimize the resource use and to maximize farmers income (Jones et al., 1997; Teng et al., 1997; Edward-Jones et al., 1998). At the regional level, crop models have been linked with GIS and spatial databases of soil and weather to determine production possibilities at the global, continental, national and sub-national level (Adams et al., 1990; WRR, 1992; Rosenzweig and Perry, 1994, Matthews et al., 1995; Penning de Vries et al., 1995; Teng et al., 1996). Most of these studies did not focus on the south Asian region although food security concerns are very serious in the region. At best, the region figures in certain studies done at the global scale. In this thesis, the goal is to apply crop simulation models for quantifying yield potential of wheat and rice in selected parts of tropics and sub-tropical regions of Asia as affected by climatic factors, genotype, inputs and management practices at field as well as regional scale. Special attention is paid to India, the most populous country of Asia, and south-eastern Asian region. Attempts have also been made to define the possible impact of climatic change on wheat productivity. The more specific objectives were:

- To simulate wheat yield potential and yield gaps in diverse agro-climatic regions of India.
- To use systems simulation to explore opportunities for growing wheat in south-east Asian tropics.
- To develop a crop simulation based framework for design of plant types for increasing yield potential.

Structure of this thesis

This thesis can be divided in three sections, each following one of the specific objectives. In section one, potential wheat yields in different regions of India are discussed. Chapter 2 describes a wheat model that simulates the effects of weather, water and nitrogen on growth and yield of wheat in tropical and sub-tropical environments. The performance evaluation of the model in various agro-environments of India and of tropics is also presented. Crop growth models such as the ones used in the present study are deterministic but there is considerable uncertainty in the crop, soil and weather inputs used. The possible impact of these uncertainties on simulated yields in different production environments is discussed in Chapter 3.

Chapter 4 describes the yield potential of wheat at field scale at many places in India as simulated by the model described in Chapter 2. It also deals with the determination of optimal water and nitrogen management strategies. In Chapter 5, yield potential of wheat is simulated for different agro-climatic regions of the country. The magnitude of the yield gap and the principal causal factors are also described in the same chapter. The possible impact that global climate change might have on wheat yields in India in different production situations is discussed in Chapter 6.

Tropical south-eastern Asia does not produce wheat at a commercial scale. Yet, there is considerable interest in its cultivation because wheat products are popular and need to be imported. Chapter 7 of section two of this thesis explores the opportunities for cultivating wheat so in different agro-environments of south-eastern Asia using a wheat model.

The final section describes the applications of crop modelling in design of new plant types. Chapter 8 discusses the optimal duration to flowering in wheat for maximising yield potential in different regions of India. Chapter 9 describes a rice crop growth model developed to assess the impact of different traits in isolation and in combination on rice yields in environments varying in nitrogen availability. A methodological framework is presented for setting the breeding goals for different traits and linking their selection to agronomic management. The implications of this on selection methodology are discussed in detail. In Chapter 10, a simple approach for designing new plant types and an integrated methodology involving crop growth models and statistical models for understanding genotype by environment interactions is elaborated for rice. Finally, the results of previous chapters are summarized and integrated in Chapter 11.

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2. Analysing the limitations set by climatic factors, genotype, water and nitrogen availability on productivity of wheat. I. Model description, parameterization and validation

Abstract

A mechanistic crop growth simulation model, WTGROWS, was developed for use in analysing effects of climatic variables and crop management on productivity of wheat in tropical and sub-tropical wheat regions of India. The model, written in CSMP and FSE, simulates daily dry matter production as a function of radiation and temperature, and water and nitrogen stresses. Crop aspects of the model are arranged in submodels covering phenological development, photosynthesis, respiration, carbohydrate partitioning, dry matter production, leaf area, grain growth and transpiration. A soil water balance model is attached to simulate water uptake and to determine water stress. Another submodel determines nitrogen uptake, distribution and N stress. Water and nitrogen stresses depending upon their severity affect various physiological processes. The model requires inputs relating to site, daily weather, soil physical characteristics and crop management. Switches allow water and/or nitrogen stresses to be terminated to establish climatically determined potential grain yield.

Various aspects of the model were validated using a large number of independent experiments. Comparison of simulated and measured quantities indicated satisfactory performance of the model in reference to water and nitrogen uptake, dry matter growth and grain yield in potential as well as water- and N-limited environments. The model appears useful as a tool for optimizing use of water and nitrogen.

Introduction

Wheat is one of the most important staple food crops of the world and is grown in a diversity of agro-climatic conditions. In India, it is grown from 15°N to 32°N, from 72°E to 92°E and from sea level to fairly high altitudes. The climate of wheat producing areas is largely tropical to sub-tropical. The soils of wheat regions vary in texture from light to very heavy clay. At present, wheat is cultivated in 17.4M ha irrigated areas and 6.3M ha rainfed areas. Average productivity of wheat ranges between 650 kg grain ha^{-1} to 4500 kg ha^{-1} depending upon the region. The total production of wheat in 1990 was 54 Mt. By 2000 A.D. the demand for wheat is likely to be 75Mt (Sarma and Gandhi, 1990) and to exceed 100Mt by 2025 A.D. There is, therefore, a need to know the productivity potential of wheat in different agro-climatic zones of the country to determine whether India can produce this much, where, and how.

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Improved agronomy has resulted in increasing national average yield of several crops in many countries (Austin, 1990). Most crops, however, have greater genetic yield potential than is being realized through current management practices. Further improvement through crop management will be facilitated by an accurate analysis of the effects of weather, soil and biological factors on crop growth. Systematic investigation of crop growth, development and yield in different agro-climatic environments is desirable, but such experimentation is costly. Crop growth simulation models are quantitative, scientific knowledge based tools that can evaluate the effects of dynamic climatic, edaphic, hydrologic and agronomic factors on crop yield and stability (de Wit, 1978; Loomis et al., 1979; Whisler et al., 1986). Such models are used increasingly for environmental characterization and agro-ecological zoning (Nix, 1987; Aggarwal, 1993), defining research priorities, technology transfer (Jones and O'Toole, 1987), estimating production potentials (Aggarwal, 1988), strategic and tactical decision making (Angus et al., 1993) and for predicting the effects of climatic change and climatic variability (Adams et al., 1990, Aggarwal and Sinha, 1993).

Several wheat models have been developed (e.g., AFRCWHEAT by Weir et al., 1984; SWHEAT by Van Keulen and Seligman, 1987 and CERES-WHEAT by Ritchie and Otter, 1985). Some of these deal exclusively with winter wheat whereas some others are overly complex. Few of them use a constant radiation use efficiency approach to predict daily biomass production. This oversimplification is often subject to errors due to feedbacks between plant sources and sinks for carbon and dynamic chemical composition of plant organs. None of the models have been well validated in the tropical and sub-tropical environments such as those of India. In this chapter, we describe a mechanistic crop growth simulation model -WTGROWS- developed to evaluate the productivity of spring wheat in tropical and sub-tropical environments. Objectives for the model are to determine climatically potential grain yields and to develop strategies for optimizing resource use particularly of water and nitrogen in a variable climate.

The Model Description and Parameterization

The primary structure of the model relating to crop growth and development is based on MACROS (Penning de Vries et al., 1989). MACROS is a general purpose, simple mechanistic model. It is well documented and its structure is relatively easy to modify. Its various submodels are in the form of modules which depending upon the interest of a user can be merged to form a crop specific model. Aggarwal and Penning de Vries (1989) adapted MACROS for determining wheat production potential in south-east Asia. MACROS does not consider the effect of N availability on crop growth. WTGROWS (WheaT GROWth Simulator) was developed to simulate growth, development and grain yield of a spring wheat crop as effected by weather, physiological characteristics, and water and nitrogen availability. The model written in CSMP as well as in FSE (Fortran Simulation Environment by Van Kraalingen, 1991) is largely explanatory. It simulates daily dry matter production as a function of irradiance, maximum and minimum temperatures, and water and nitrogen availability. Crop aspects of the model are arranged in submodels covering development, photosynthesis, respiration, carbohydrate partitioning, dry matter production, leaf area, grain growth and transpiration. A soil water balance model is attached to simulate water uptake and to determine water stress. Another submodel determines nitrogen uptake, distribution and nitrogen stress. Various crop processes are affected by water and nitrogen stresses. A relational diagram of the flows of material and information among various sub-models is depicted in Figure 2.1. The major differences between MACROS and WTGROWS are listed in Table 2. 1. In this chapter, only those processes are described in detail where WTGROWS differs significantly from MACROS in approach and/or thresholds and rate constants.

Table 2. 1. Major differences in MACROS and WTGROWS. The two models also have differences in rate constants and thresholds, and some minor differences in other processes which are described in the text.

PROCESS	MACROS	WTGROWS
Structure	Modular, non crop specific	for wheat alone
Seedling emergence	Not considered	Function of soil water and temperature
Maximum rate of increase in rooting depth	constant	varies with development stage, maximum rooting depth and crop duration
Allocation of potential water demand to rooting depth	Equal	Unequal depending on exponential root length density distribution
Water stress effects	Photosynthesis, phenology, root:shoot ratio	Photosynthesis, phenology, root:shoot ratio, partitioning within the shoot, senescence
Soil N balance	Not considered	Included
Crop N balance	Not considered	Included
N deficiency effects		Photosynthesis, respiration, partitioning, senescence, phenology

Crop development

Phenology is divided in three major phases:

1) Sowing to seedling emergence
2) Seedling emergence to anthesis
3) Anthesis to maturity

The duration of these phases is under strong environmental control. Temperature and daylength are the major climatic factors regulating duration (Robertson, 1968). The sub-model requires inputs of sowing date, site latitude and daily mean temperatures (arithmetic mean of maximum and minimum temperatures). Daylength, dependent upon site latitude and day of the year, is estimated by astronomical calculations (Penning de Vries et al., 1989).

Sowing to seedling emergence The duration of this phase may be common to a range of cultivars and is described well in terms of thermal time, i.e. mean temperature × duration of the phase (Angus et al., 1981a). It was estimated from the work of Pushkala (1982) that at a depth of 4 cm, thermal time required is 65 degree-days above a base temperature of 3.6 °C. For each cm $\pm$ change in soil depth, thermal time changes by $\pm$17.4 degree-days.

Seedling emergence to anthesis The following model was used to estimate crop duration up to anthesis:

$$D = a + bT + c\,L \qquad (2.1)$$

where

D rate of development (day^{-1}),

T mean temperature (°C),

L daylength (h) and

a, b, c are constants.

Perry et al. (1987) compared five different additive and multiplicative linear and non-linear models and found this simple model adequate to explain variation in rate of development of a number of wheat cultivars in diverse environments. The model was used by Loss et al. (1990) for predicting optimal time of anthesis in south-western Australia. In the present study, parameters for Equation 1 were determined using data of 46 crops of widely used, semi-dwarf, medium maturity Indian cultivar, Kalyansona (AICWIP, 1969; Dadwal, 1983; Chakravarty and Sastry, 1983; Bagga and Rawson, 1977; Rahman and Wilson, 1977). These crops were sown over several crop seasons, from 1969 to 1983, across diverse locations ranging from 17.3°N to 31°N as well as in controlled environments. In the total data set, duration of the pre-anthesis phase ranged from 36 to 108 days, mean temperature from 12.5 to 24.5 °C and daylength from 8 h to 24 h. The following relation was generated from Equation 1 using the Kalyansona data.

$$D\ (day^{-1}) = -.0171 + .0011T\ (°C) + .0010L\ (h),\ (n{=}46;\ r^2{=}.89) \qquad (2.2)$$

The above regression can also be used to estimate photothermal time for predicting the time taken to flower (Roberts and Summerfield, 1987). By analogy with thermal time, photothermal time is given by 1/b but the base temperature (Tbase) above which it is accumulated varies with photoperiod and is given by the following:

$$Tbase = -a + c\,L\,/\,b \qquad (2.3)$$

Accordingly, photothermal time required by Kalyansona from seedling emergence to anthesis is 909 °Cd above a base temperature, which changes with photoperiod. The base temperature was calculated to be 6.45, 5.54, 4.64 and 3.73 °C at 10, 11, 12 and 13 h mean photoperiod, respectively. Crop development of cultivars earlier or later than Kalyansona can be simulated by varying either thermal time or base temperature.

Anthesis to maturity Thermal time for this phase is taken as 393 °C above a base temperature of 7.5 °C (Saini and Dadwal, 1986). Photoperiod effects and cultivar differences in this are generally small and ignored (Angus et al., 1981b; Saini and Dadhwal, 1986).

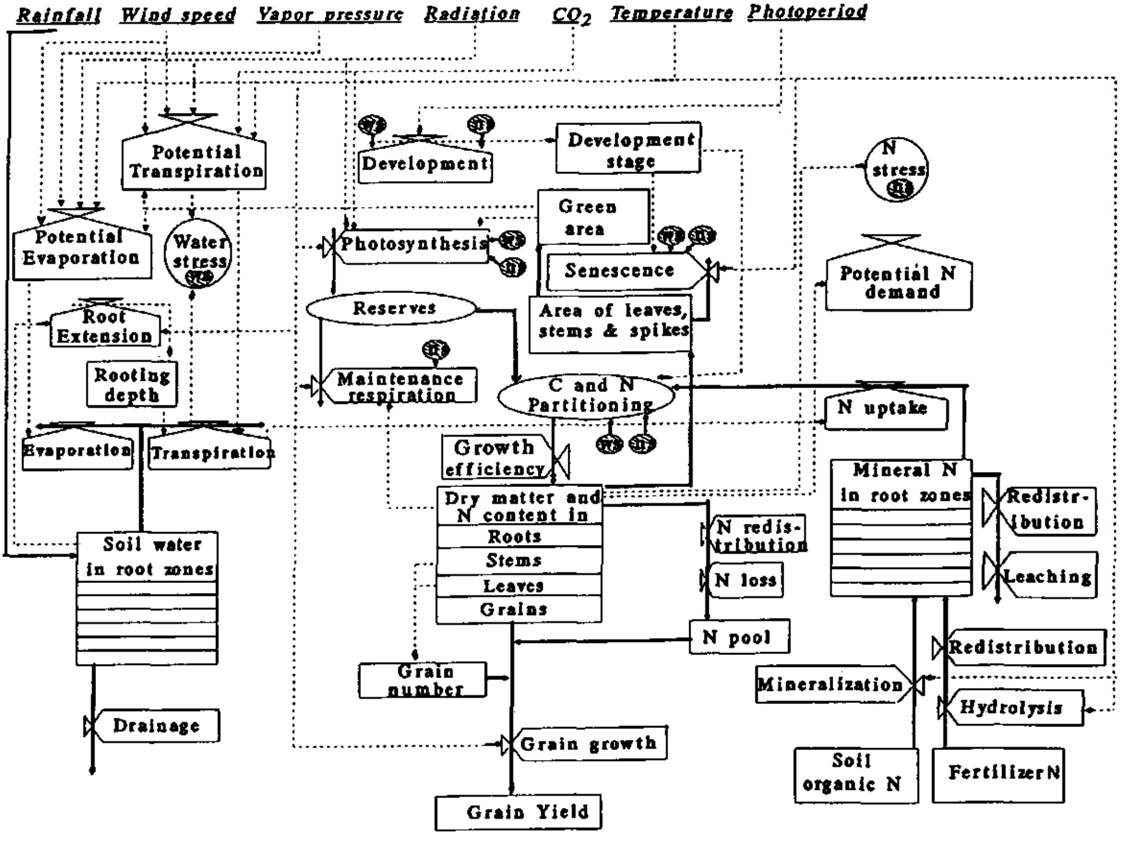

Figure 2.1. A relational diagram explaining interrelationships and feedbacks amongst major physiological processes and their interactions with soil water and nitrogen availability in WTGROWS. Dashed lines indicate effect of climatic factors and information flow and solid lines describe flow of material. Valves are rates, rectangles are quantities and circles are auxiliary variables. To avoid complexity in representation, feedbacks loops of water and nitrogen stresses on crop physiological processes are shown as small circles only.

Dry matter production

The leaf and root weights at seedling emergence are initialized. These are estimated from seeding rate. Half of the seed weight is assumed to be lost in respiration. The balance is partitioned equally between roots and leaves. For simulating further increase in dry matter, the crop is treated as an intact unit. Individual plants/tillers are not simulated.

Photosynthesis Gross canopy photosynthesis is calculated depending on the distribution of light within the canopies, the radiation absorbed by the canopy and photosynthesis light response curve of leaves (Spitters et al., 1989). The light distribution depends on the light intensity above the canopy and on the extinction coefficients for direct and diffuse radiation. The direct and diffuse components are calculated following Spitters et al. (1986). Radiation absorption is calculated for three depths in the canopy and at three moments of the day. The rate of gross photosynthesis of an individual leaf is calculated as a function of the light saturated rate of CO_2 assimilation (PLMX), initial light use efficiency (PLEI), and radiation absorbed. PLMX is affected by leaf N content or specific leaf area as described in a later section. Leaf photosynthesis is also affected by temperature (Aggarwal and Penning de Vries, 1989). In the model, both PLMX and PLEI increase linearly by 29% as CO_2 increases from 340 ppm to 660 ppm (Kimball, 1983; Cure and Acock, 1986). The negative feedback of reserves on photosynthesis is included in WTGROWS following Van Keulen and Seligman (1987).

Maintenance respiration It is equivalent to 3.0, 1.5, 1.5, 1.1 and 1.0% per day of the dry weights of leaves, stems, ear structures, roots and grains, respectively at 25 °C (Penning de Vries and Van Laar, 1982). In addition ten percent of daily gross photosynthesis is assumed to be consumed in metabolic activity (Penning de Vries et al., 1989). The effect of temperature on respiration is accounted for with a Q_{10} value of 2.

Carbohydrate Partitioning The total amount of carbohydrates available each day for plant growth is calculated by subtracting the carbohydrates used in maintenance respiration from the total gross assimilation. These carbohydrates are then partitioned into leaves, stems, spike structures, grains and roots as a function of development stage based on field experiments of Aggarwal (1983) and Fischer (1983). A fraction of carbohydrates partitioned to the stems is treated as non-structural reserves following the partitioning coefficients proposed by Van Keulen and Seligman (1987). This scheme of partitioning generally results in 30 - 35% of simulated weight of stems at anthesis in the form of non-structural reserves (as observed in field-grown plants by Austin et al. (1977) and Aggarwal and Sinha (1984)). After anthesis, in addition to current assimilates, 10% of the previously accumulated reserves is mobilized every day and used for grain growth.

Growth respiration After carbohydrates are partitioned to different plant parts, they are converted into structural material. The growth respiration is simulated by assuming that the percentage of all other constituents except carbohydrates and proteins is fixed. The protein content is regulated by N concentration calculated in the model. The carbohydrate requirement and CO_2 production is then determined following Penning de Vries et al. (1989).

Leaf area Total photosynthetic area consists of leaf laminas and surface areas of stems, sheaths and spikes. Leaf lamina area changes proportionally with leaf growth rate, its value is obtained by multiplying the increment in leaf weight by the specific leaf area (SLA). Leaves formed early in the plant life cycle are thinner than leaves formed later and this is simulated by adjusting SLA. The photosynthetic area of stems, sheaths and spikes is estimated between 10 to 100% of green leaf lamina area (Fischer, 1983). In the present model, the photosynthetic area of non-lamina structures increases from nil to 50% of the leaf lamina area as the crop development progresses from stem extension phase to anthesis. The photosynthetic characteristics of these non-lamina green areas is assumed to be same as those of leaves.

Simulation of senescence is based on several empirical constants. The loss in leaf weight due to aging and tiller mortality is assumed to commence once stems start expanding. At this stage, the daily rate is taken as 0.3% of the current leaf weight; subsequently, it increases linearly to 0.8% per day by booting stage (Goutzamanis and Connor, 1977). Shading in dense stands accelerates senescence. This is simulated by increasing the rate of senescence if leaf area index (LAI) exceeds a critical value of 4.0. The death rate due to shading is zero below this critical LAI and increases linearly to a maximum of 3% per day of leaf dry weight till LAI becomes 8.0 (Van Keulen and Seligman, 1987). The common decrease in leaf area after anthesis is simulated using a function that reduces leaf area quadratically as a function of development stage. High temperature after anthesis accelerates senescence and the increased rates are similar to those used by Van Keulen and De Milliano (1984) for wheat. The green area of stems, sheaths and spikes also decreases quadratically but this senescence starts when 60% of the post-anthesis development stage is over.

Grain yield

In WTGROWS, the source-sink balance is considered in determining dry matter accumulation by grains. Grain number (GNO, sink size) is dependent on total or spike dry matter at anthesis (Fischer, 1985; Vos, 1981). Values ranging from 12 to 24 grains g^{-1} of dry matter at anthesis have been reported (Fischer, 1985; Vos, 1981; O'Leary et al., 1985). There are significant cultivar differences as can be estimated from the data of Aggarwal et al. (1986a). In the model a mean value of 18 grains g^{-1} dry matter at anthesis is assumed.

Once the grain number is determined at anthesis, the rate of carbohydrate accumulation by grains is determined by cultivar, temperature, potential grain-filling rate and the level of available carbohydrates per grain. In the model, growth of each grain is simulated separately. Dry weight accumulation by kernels shows a lag period lasting 4 to 5 days after anthesis followed by a long period of linear growth. During the lag phase, grain growth is small and is estimated to be 0.4 g g^{-1} grain weight day^{-1} at 16 °C and with a Q_{10} of 2.0 (Vos, 1981). It is assumed that the initial grain weight at anthesis is 0.5 mg. In the linear phase, potential grain growth is dependent upon cultivar and temperature. In the model, this rate is set to 2.0 mg day^{-1} at 16 °C with a Q_{10} of 1.5 (Vos, 1981). This results in grain-filling rates similar to those reported by Kumar and Singh (1981) and found by Aggarwal et al. (unpublished) for several Indian wheat cultivars. At both stages, actual rate of grain growth is limited by the potential grain filling rate as determined above or by carbohydrates actually available for grain growth. If the amount of available carbohydrates is greater than the potential grain filling rate, excess carbohydrates are transferred to the reserves pool. Grain growth is terminated when grain weight reaches potential grain weight or by the end of development stage 2. Potential grain weight is set to 47 mg for semi-dwarf wheat cultivars (Fischer, 1983).

Effect of water deficit

Soil water balance The volumetric water percentage at field capacity, saturation, wilting point and air dry point of each layer is specified. The available water at the beginning of simulation is initialized. Simulation of water balance is done using L2C and L2SU modules of MACROS. The structure of the program was changed to simulate the water balance of up to 10 soil horizons.

Rooting depth Initial rooting depth is set at the time of seedling emergence. Further downward growth is determined by a potential rate of rooting depth growth per day and maximum rooting depth. This rate is dependent upon the development stage (Borg and Grimes, 1986) and is limited by a genetically determined upper limit. The maximum rooting depth is made dependent upon thermal time – long duration cultivars have relatively deeper roots. Rooting depth does not increase after flowering and is also limited by the maximum soil depth. Root extension growth rate is multiplied with a factor to simulate the effect of water stress. This factor is the ratio of average available soil water fraction in the root zone and a critical value of soil water fraction derived from atmospheric evaporative demand following Doorenbos and Kassam (1979). The effect of soil temperature is considered analogous to that of temperature effect on photosynthesis; there is no effect between 10 and 25 °C.

Water uptake Potential transpiration is estimated using SUEVTR subroutines of Penning de Vries et al. (1989). This sets the crop demand for water on any given day. The rate of transpiration is dependent on daily irradiance, temperature, vapour pressure, leaf area index and leaf resistances. Actual rate of water uptake is dependent upon this potential rate and availability of water in the soil profile. It is less than the potential rate of transpiration when soil water content is below a critical threshold value. Potential transpiration is allocated to various soils layers on the basis of exponential root length density distribution function used in CERES model (Ritchie and Otter, 1985) and parameterized following Kalra (1986). The actual uptake from a given soil layer starting from the surface layer is computed by multiplying this potential demand allocated to that layer with the water stress effect. The latter is calculated based on available soil water and a critical value of soil water, which varies with potential evapotranspiration (Doorenbos and Kassam, 1979). Availability of water to plants is reduced proportionately if soil water is less than the critical value. If the allocation of potential transpiration to a given layer is more than the actual uptake, then the unsustainable load (allocated potential transpiration - actual water uptake) is distributed to lower layers having roots above a critical value (parameterized to 5% of total roots by sensitivity analysis). Thus, the lower layers have to meet their assigned load as well as the unsustainable load of the top layers. This pattern of demand allocation simulates situations where sufficient root density is present in relatively dry surface soil layers but the water withdrawal is greater from wetter lower layers (Taylor and Klepper, 1971). The procedure is continued till the entire root zone is covered. Root water uptake from various soil layers is integrated for computing actual transpiration.

Effect of water stress on growth processes Water and turgor potentials are known to affect several processes (Hsiao, 1973). In the present model, water potential is not simulated. Water stress is determined as the ratio of actual water uptake and potential transpiration. A decrease in soil water availability reduces the rate of germination. This is simulated by making thermal time and base temperatures dependent upon available water fraction in soil surface layer. Water stress increases thermal time required but decreases base temperature. Water deficiency in the crop decreases transpiration and raises canopy temperature (Idso et al., 1980) accelerating phenological development. On an average, water stress prepones flowering of a wheat crop by 3 to 10 days depending upon the severity of stress (Aggarwal et al., 1986b). An empirical relationship is built in the model that accelerates pre- and post-anthesis development rate up to a moderate level of stress.

The rate of gross photosynthesis decreases in proportion with transpiration. The model does not consider any effect of water stress on respiration. Root:shoot ratio increases with stress (Lupton et al., 1984). In the model, this is simulated by reducing the allocation of carbohydrates to leaves depending upon the severity of stress. Ninety percent of this resulting 'excess' carbohydrates is allocated to roots and rest is stored in the stems (Van Keulen and Seligman, 1987). The rate of leaf senescence is accelerated depending upon the level of water stress. Mild stress does not have a significant effect but moderate and severe stress increase the rate of senescence by 30 to 50%. The stress does not have any direct effect on sink size; the effect on total grain number is mediated through their effect on dry matter production.

Effect of nitrogen deficiency

Soil N availability Total soil N is subdivided into organic and inorganic fractions. Both fractions are initialized for each layer of the profile at the beginning of simulation. During the course of crop growth, N availability changes due to net mineralization, inorganic fertilizer application and crop N uptake. The model does not simulate the effect of additions of organic matter. Mineralization of natural organic N to NO_3 is considered as a single step (bypassing steps of NH_4 accumulation). The rate of this is a function of potential mineralization rate (function of total N content in the soil), ratio of soil water to field capacity and a temperature coefficient determined from daily average temperature (Littleboy et al., 1989). Fertilizer applied in the form of NO_3 or NH_4 is assumed to become a part of the soil NO_3 pool immediately. Urea, if applied, is hydrolysed depending upon a rate constant, which depends on soil water content and soil temperature. From the data of Patra and Jain (1984), it was calculated that 25% of urea applied is hydrolysed in 1 day and all urea is hydrolysed in 4 days after application provided the temperature is optimal and there is no water stress. This rate constant is used in the model. The effect of suboptimal water and temperature on this rate constant is computed following Ritchie and Otter (1985).

'Available' nitrogen as determined above is not actually available for crop uptake. A considerable fraction is immobilized into bacterial biomass or adsorbed by soil particles (Srivastava et al., 1984). The amount of N immobilized depends on the residue availability and thus cropping practice. Up to 20% N can be lost by volatilization affecting nitrogen fertilizer efficiency (Sarkar et al., 1991). There are numerous reports suggesting that only 30 to 40% of the total soil mineral nitrogen, including fertilizer N, is taken up by the crop (Goswami et al., 1984, Sachdev et al., 1990). Detailed mechanistic models are available to predict N immobilization and soil N transformation and losses but their input data requirement is large and the crop model becomes overly complex (Van Keulen and Seligman, 1987). To avoid this, two empirical constants are built in the model to scale down the soil and fertilizer N availability for crop uptake. Following the studies of Singh and Sharma (1990) on utilization of available nutrients, soil N availability is assumed to be 40% of the total soil mineral N and fertilizer N availability as 50% of the applied amount. The net soil N availability is then determined as follows:

$$\text{N initial(i,j)} = \text{Mineral N(i,j) at sowing} \times 0.4 + \text{N applied} \times 0.5 \qquad (2.4)$$

$$\text{Net N available(i,j)} = \text{N initial (i,j)} \;\square\; \text{N drained(i,j)} + \text{N mineralized(i,j)} + \text{N gained from upper layers (i,j)} \;\square\; \text{crop N uptake} \qquad (2.5)$$

where subscript *i* refers to soil layer and *j* refers to time. The empirical constants represent a weakness in the model. Simple mechanistic models for predicting soil N availability are needed.

Soil N movement Because all soil mineral nitrogen is assumed to be in the NO_3 form which is very mobile, movement of water decides N movement as well. N is assumed to be in solution and moves to lower layers with drainage. Some N can also move upwards with soil evaporation. The net N available in a particular layer, therefore, is the balance of N initially available, N additions from upper layers and N losses to the lower layers.

N uptake by roots The rate of N uptake is dependent upon crop N demand, phenological age, soil N availability, transpiration, rooting depth and soil water status. It is assumed that nitrogen is taken up in the form of NO_3 along with water uptake. Total crop N demand is first allocated to different soil layers in proportion to transpiration load being met from various layers. The actual crop N uptake is then the minimum of this allocation and actual N availability in that particular layer. The total soil N supply to the crop is the sum of N uptake from each layer. This method of determining N uptake simulates situations where N in some soil layers is not available to the crop because of limited water withdrawal from these layers. The maximum rate of N uptake is limited by the translocation capacity of the plant. It is dependent upon a potential uptake rate of a closed canopy, dry weight of leaves and stems and a factor to convert these weights to relative area, following Van Keulen and Seligman (1987).

Crop nitrogen uptake The rate at which nitrogen is taken up by the crop is governed by crop demand, soil supply and transport capacity of the plant. In estimating demand, the potential nitrogen that different plant parts require is determined. This depends on rate of growth as determined earlier and the maximum concentration of N [Nm] that organ can accumulate. The latter is the N concentration in plants growing on an unlimited supply of soil N and with no biotic and abiotic stresses. [Nm] for different plant parts varies with crop age and is parameterized following field experiments of Nair (1975) conducted with cultivar

Kalyansona. It is 6% in leaves during seedling stage; decreases gradually to 3.5% by anthesis and 1.0% by maturity. [Nm] of stem varies from 4% at vegetative stage to 0.3% at maturity. In roots, [Nm] is 3% at seedling stage, 1% at anthesis and 0.5% at maturity. [Nm] of grains is 3% immediately after anthesis and declines to 2.75% at maturity.

The N demand of any plant part at a given day is the difference of its [Nm] value and current actual N content. Total N demand is thus the sum of current demand and previously accumulated N deficiency of all plant organs. There are conflicting reports in literature on N uptake after anthesis (see Nair and Chatterjee, 1992 for a review). In the present model, N uptake is prevented shortly after anthesis by setting crop N demand to zero. Grain nitrogen demand is assumed to be met by translocation after anthesis from vegetative plant material.

The potential N demand of grains is a function of sink size (number of grains), potential rate of N accumulation in a grain and temperature. N accumulation by grains shows a lag period of 4 to 5 days after anthesis followed by a long period of linear growth analogous to that of carbohydrates accumulation (Vos, 1981). In the linear phase, the potential nitrogen accumulation is dependent upon cultivar and temperature. In the present model, this rate is set to 0.04 mg grain^{-1} day^{-1} at 16 °C with a Q_{10} of 1.5 (Vos, 1981). Total grain N demand is the product of number of grains ha^{-1} as determined earlier and N accumulation rate in grains.

Distribution of nitrogen Net N uptake is distributed to root, stem, leaves and spike structures in strict proportion to their relative demand. The net N loss from the crop due to senescence is restricted to the residual N content of senescent plant parts.

Recent reports suggest that N can also be lost from aerial plant parts directly to the atmosphere (Wetselaar and Farquhar, 1980). Such losses are more pronounced immediately after anthesis (Harper et al., 1987). This is possibly related to the inadequate capacity of the sink to accumulate all N that is potentially mobilizable (Harper et al., 1987; Parton et al., 1988). In the model, this is considered by allowing for such losses after anthesis, subject to the condition that N potentially available for grain filling exceeds N accumulation of grains. If this condition is met, then a fraction (parameterized to 5% in the model) of mobilizable N that could be transferred is lost. In general, this approach results in a loss of 5 - 15 kg N ha^{-1} from aerial plant parts after anthesis depending upon the N content of leaves.

Mobilization of nitrogen to grains It is assumed that all nitrogen of plant parts above non-mobilizable (residual) portion is potentially available for translocation to grains. The residual fraction amounts to 10 - 15% of the N concentration in an organ. Because uptake has ceased, mobilizable nitrogen sets the upper limit of N available for grain growth. The amount of N actually available, however, also depends on the rate of protein decay. A time constant of 10 days has been proposed by Penning de Vries (1975) for the completion of this hydrolysis.

The actual rate of N accumulation in grain is limited by potential N demand of grains and the availability of mobilizable nitrogen pool. Nitrogen actually transferred to grains is drawn from different plant parts in proportion to their relative mobilizable N. The model does not allow grains to accumulate more than the optimal N content; the later is the product of dry matter and optimal N concentration in the grains.

The actual N content in each plant part is the balance of the N partitioned to the organ, N transferred to the grains, and N lost in senescent tissues. Depending upon the total weight of that organ, actual N and protein concentration is computed.

Effect of nitrogen stress on growth processes Nitrogen stress is determined based on maximum, minimum and current levels of N in different plant parts, analogous to actual/potential transpiration ratio used for determining water stress factor. N stress effect has a value of zero (maximum N stress) when actual mobilizable nitrogen is zero and linearly approaches a value of 1.0 when actual nitrogen approaches maximum value (no N stress).

N stress in the crops decreases transpiration and raises canopy temperature accelerating phenological development. The effect is same as that of water stress. Amongst water and nitrogen stresses, the one that is more severe affects the rate of crop development. PLMX decreases as nitrogen concentration decreases from an optimal level. Both linear (Van Keulen and Seligman, 1987) and curvilinear (Evans, 1983) response functions have been established. In the model, the rate of photosynthesis changes curvilinearly. Accordingly, PLMX is 36 kg ha^{-1} h^{-1} when leaf N content is 20 kg ha^{-1} and above. At 16 and 8 kg N ha^{-1} leaf area, PLMX is 32 and 20 kg ha^{-1} h^{-1}, respectively. With further decrease in leaf N content, PLMX decreases linearly and becomes zero at 0.2 kg N ha^{-1} leaf N content. The model does not simulate N balance for estimating climatically determined potential growth (done by appropriate switch setting). In that case, PLMX is made dependent upon specific leaf area following Khan and Tsunoda (1970). The maintenance requirement of all organs decreases in proportion to N stress experienced by them. N stress is assumed to affect partitioning of carbohydrates and senescence in the same way as water stress does. Amongst water and nitrogen stresses, the one that is more severe affects the partitioning.

Validation

The performance of the model was tested against a large number of independent data sets collected by several authors. Because the primary interest of developing this model is the analysis of productivity, more attention was paid to testing model's prediction of productivity in a range of environments.

The model requires inputs of daily weather data, management practices and cultivar specific coefficients (Table 2.2). Because these are not precisely known for most cultivars, we have used, unless otherwise specified, a standard set of inputs for medium duration high yielding cultivars (Table 2.3), most commonly used in different experiments.

Potential Production Environments

The performance of the model was evaluated in climatically potential production conditions, i.e., when crop is not effected by any biotic and abiotic stresses. Thus, in this environment the primary determinants of crop growth are temperature and radiation. The model simulates such situations by switching off the effects of water and nitrogen stresses on crop growth and development.

Table 2.2. Inputs required in WTGROWS.

Input	Unit
Site data	
Latitude	degree
Elevation	m
CO_2 concentration	ppm
Daily Weather data	
Maximum temperature	°C
Minimum temperature	°C
Solar radiation	MJ m^{-2}
Rainfall	mm
Wind speed	km h^{-1}
Vapour pressure	kPa
Soil characteristics	
Soil depth	m
Number of horizons	
Thickness of a horizon	m
Volumetric soil water content for each horizon at	
Saturation	fraction
Field capacity	fraction
Wilting point	fraction
Air dry level	fraction
Management data	
Sowing date	day of the year
Seed rate	kg ha^{-1}
Sowing depth	m
Irrigation date	day of the year
Irrigation amount	mm
Fertilizer application dates	day of the year
Fertilizer amount applied	kg
Fertilizer type	1 for urea, 2 for others
Fertilizer use efficiency	fraction
Soil mineral N use efficiency	fraction
Soil characteristics at sowing for each horizon	
water content	fraction
mineral N	kg ha^{-1}

Several data sets were used to evaluate the outputs of the model. Saini and Nanda (1983) and Saini et al. (1980) reported leaf area and dry matter growth over time for wheat grown in four cropping seasons 1971-72, 1975-76, 1976-77 and 1977-78 at New Delhi. These data were used for evaluating the simulation of leaf area and dry matter growth. Time to anthesis was recorded by Aggarwal et al. (unpublished) for 4 cultivars in 5 dates of sowings. This data was used for evaluating the crop duration to anthesis. All these crops were grown with optimal management providing for adequate amount of irrigation and fertilizer. Detailed crop growth data from any location other than New Delhi could not be obtained.

Table 2.3. Genotypic characterization required in WTGROWS and a list of parameters for a 'standard' semi-dwarf cultivar.

GENOTYPIC CONSTANTS	UNITS	'standard' DATA
Thermal time for		
Germination	degree-days	65
Seedling emergence to anthesis	degree-days	800
Anthesis to maturity	degree-days	393
Maximum gross photosynthesis rate	kg ha^{-1} day^{-1}	40
Specific leaf area constant	Ha kg^{-1}	.002
Grain number	number dry wt at $anthesis^{-1}$ (no g^{-1})	18
Grain filling rate at 16 °C	mg $grain^{-1}$ day^{-1}	2
Potential grain weight	mg $grain^{-1}$	47
Maximum root extension rate	m day^{-1}	0.03
Maximum rooting depth	m	1.8
Nitrogen accumulation rate in grains	mg $grain^{-1}$ day^{-1}	0.04

An extensive data base on grain yield was assembled to represent diverse environments of Indian wheat growing regions. This data set was used for testing the model's prediction of grain yield. Annual Reports of the All India Co-ordinated Wheat Improvement Project (AICWIP) for the period 1968-1988 provided the data on maximum grain yield obtained at many locations throughout India. These trials receive optimal management to obtain the best expression of the plant material. Although new cultivars are released continuously, no significant change in wheat yields has been recorded over years in different locations (S.K. Sinha et al., unpublished). For the validations, it was therefore assumed that these yields represent climatically potential grain yields. The choice of crop season and location used for validation was restricted by the availability of actual daily weather data. The final data base consisted of 59 crops sown on different dates and seasons at New Delhi (28.4°N, 77.1°E), Hissar (29.1°N, 75.4°E) and Pantnagar (29°N, 79.30°E) in northern India; Patna (25.3°N, 85.15°E) in eastern India; Indore (22.43°N, 75.5°E) in central India; Akola (20.42°N, 77.2°E) in western India; and Coimbatore (11°N, 77°E) in southern India. In addition, data from 12 crops at Los Baños (14°N, 122°E), Philippines (Aggarwal et al., 1987) were also included.

Crop duration Measured duration to anthesis varied between 64 to 112 days and simulated duration between 64 to 109 days depending upon the cultivar. Figure 2.2 shows that simulated durations were reasonably close to the measured values irrespective of the cultivar. The intercept of the regression was low but the slope was 0.918 indicating slight under-prediction for long duration cultivars. The standard error of the estimate was 2.63 days only.

Leaf area index (LAI) Simulated LAI in 1971-72 crop season was similar to the observed LAI at all times irrespective of the growth stage (Figure 2.3). In 1975-76 crop season, the model predicted a higher LAI than was measured during first 70 days of crop growth; later the two values were similar. Simulated LAI in the next two crop seasons was again quite close to measured values during the entire life cycle.

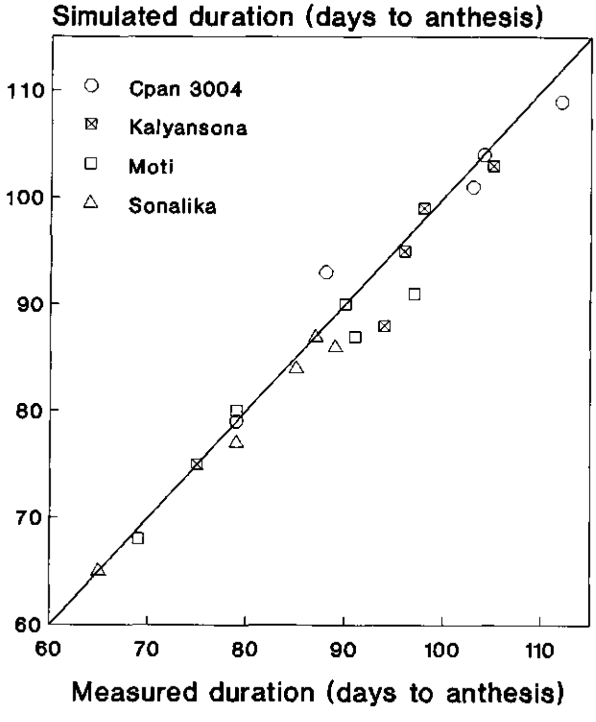

Figure 2.2. Comparison of measured and simulated crop durations to anthesis in 4 wheat varieties sown on 5 dates.

Dry matter The comparison of simulated *vs.* measured dry matter changes over time are made for 1971-72, 1975-76, 1976-77 and 1977-78 crop seasons (Figure 2.4). In all cases, the model estimated total dry matter realistically.

Grain yield Measured grain yields varied between 1.2 and 7.4 t ha^{-1} and simulated grain yields between 1.7 and 7.7 t ha^{-1}. Mean measured and simulated grain yields were 4.4 ± 1.6 and 4.7 ± 1.1 t ha^{-1}, respectively. Figure 2.5 illustrates the scatter of simulated and measured grain yields around the regression line and 1:1 line. At most places, simulated grain yields were reasonably close to measured yields with no point outside $\pm$ 1 standard deviation of mean observed yields. For certain late sowings, the measured yields are larger than the simulated ones. This was possibly due to use of standard genetic coefficients (cultivars) in simulation, while in practice, cultivars do change with location and time of sowing.

The simple regression of simulated yields over observed yield (Figure 2.5) yielded an intercept reasonably close to zero, a slope of almost one and a high regression coefficient. Standard error of this prediction was 0.63 t ha^{-1} which is 11.3% of the observed mean grain yield. The agreement between simulated and measured grain yields establish the model's robustness in predicting climatically potential crop growth and yield for these tropical locations, seasons, and sowing dates contrasting in temperature and radiation.

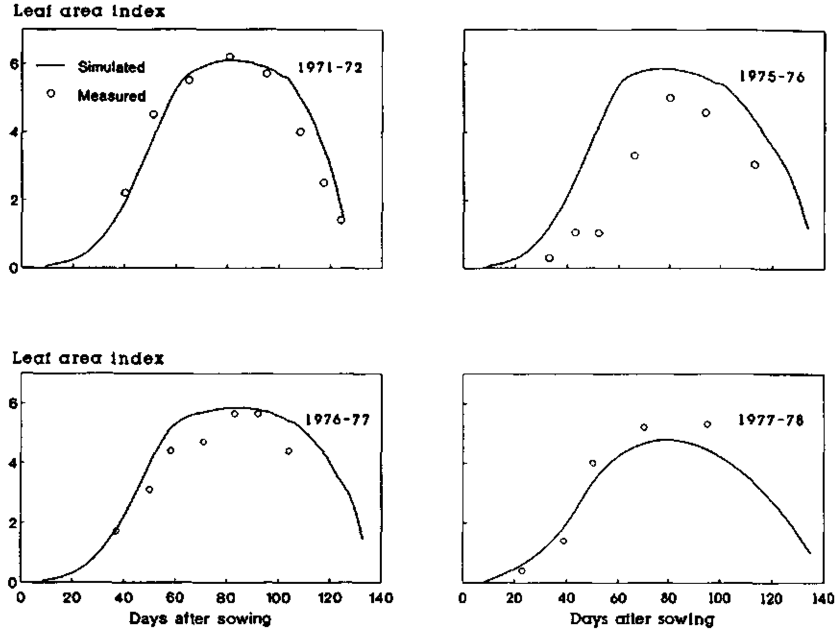

Figure 2.3. Comparison of measured and simulated course of leaf area index with time in four wheat crops grown in different seasons at New Delhi.

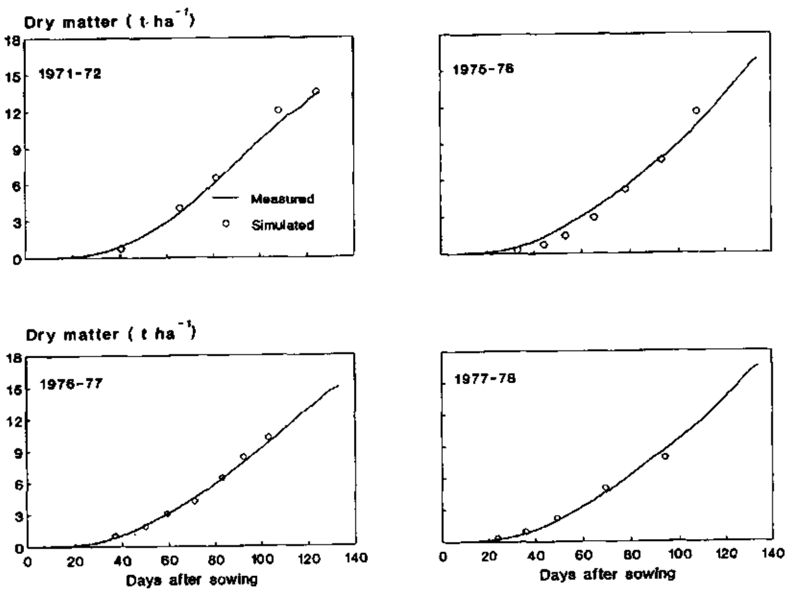

Figure 2.4. Comparison of measured and simulated course of dry matter with time in four wheat crops grown in different seasons at New Delhi.

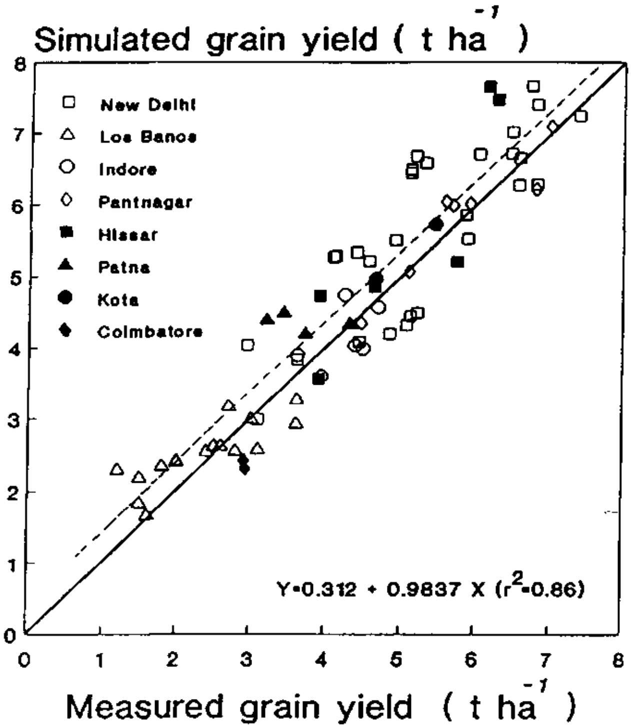

Figure 2.5. Comparison of measured and simulated grain yields in potential production environment for several contrasting locations. Crops were grown in different seasons and with different sowing dates by independent workers. Also shown are 1 :1 line (solid line) and the parameters and line of regression (dashed line) between simulated and observed values.

Water- and Nitrogen-Limited Environments

A database of measured data was assembled from a large number of independent experiments to evaluate the performance of the model in water- and nitrogen-limiting conditions. Brief details of these experiments are given in Table 2.4. Experiments 1 to 4 were conducted in different seasons (radiation, temperature) in New Delhi (28°N). Experiment 1 covered a range of treatments with low and high N fertility at different levels of water availability and thus provided a range of treatments where interaction between water and N availabilities was significant. Temporal changes in LAI, dry matter and ET were recorded in Experiment 2. The Experiment consisted of 4 treatments - rainfed (T4), water stress during vegetative stage (T2), water stress during reproductive stage (T3) and fully irrigated (T1). Experiment 3 also had treatments with varying levels of water stress. Experiment 4 was conducted in lysimeters over a period of several crop seasons with irrigation and modest applications of N fertilizer. Experiment 5 was conducted in Jabalpur (22°N) and consisted of treatments varying in degree and stage of water stress. The soils of New Delhi are sandy loam whereas those at Jabalpur are clayey. The treatments in these experiments differed in initial water and nitrogen content in the profile, and/or the amount of water and nitrogen applied during the crop season resulting in different levels of water and N stresses and their interactions at different stages of crop growth and development. As a consequence, considerable variance was recorded in LAI, dry matter, ET and yield. A representative soil water and N profile was constructed based on expert knowledge for the few experiments where initial water and N profile were not available. Some experiments reported temporal changes whereas other reported data at maturity only. Since the deviation between simulated and measured crop durations to anthesis were occasionally significant in water stress treatments (data not shown), the value of thermal time for anthesis (TTVG) was calibrated for each Experiment. The model outputs of temporal changes in LAI, dry matter, ET, N concentration and seasonal changes in dry matter, ET, N uptake and grain yield were compared with the measured data.

Table 2.4. List of experiments and their details used for evaluating model's performance in water- and nitrogen-limited environments. Experiments 1 to 4 were conducted in New Delhi and Exp. 5 at Jabalpur. Treatments differed in stages of irrigation and/or fertilizer application.

Exp.	Date of sowing	No of treatments	No of irrigations	N applied (kg ha^{-1})	Reference
1	13 Nov 1990	16	0,1,1,5	0,60,120,180	Aggarwal et al., 1993 unpublished
2	16 Nov 1984	4	0,1,2,4	100	Kalra, 1986
3	21 Nov 1986	6	0,1,5	100	Pillai, 1988
4	4 Dec 1982	1	4	100	A.K.Singh et al., 1993 unpublished
4	1 Dec 1983	1	4	100	
4	3 Dec 1984	1	4	100	
4	3 Dec 1985	1	4	100	
4	9 Dec 1986	1	4	100	
4	2 Dec 1987	1	4	100	
5	26 Nov 1976	4	0,1,1,4	100	Tomar et al., 1981

Evapotranspiration Seasonal changes in measured and simulated ET were compared for all treatments of Experiments 2 and 4. In Experiment 4, in all the six crop seasons, for most of the period, simulated ET was very close to measured ET. Figure 2.6A presents the results for crop seasons 1985-86 and 1987-88. There was slight overestimation of ET in 1987-88 during pre-flowering phase but subsequently there was no significant difference between two ETs. The model slightly underestimated ET particularly after flowering in 1985-86. In Experiment 2, at all levels of stress, the model simulated ET matched with observed ET at all times during the crop season except in post-flowering phase when there was a small underestimation of ET in irrigated and partially irrigated treatments (Figure 2.6B). In severely stressed treatment T4, there was good agreement between simulated and measured ET but simulated crop matured 80 days after sowing whereas measurements indicated a crop duration of 100 days. Nevertheless the ET between 80 and 100 days after sowing was small.

Simulated ET at maturity was plotted against measured ET for a number of experiments (Figure 2.7A). With the exception of few treatments particularly of Experiment 2, most points were close to the 1:1 line. When ET was low (severe water stress treatment of Experiments 1 and 5), there was one treatment where simulated ET was much lower than the measured ET. For all other treatments up to a measured ET of 350 mm there was a good agreement; subsequently the model underestimated ET. This behavior was also reflected in the statistical parameters of the regression between simulated and measured ET (Figure 2.7). Standard error of this estimate was 30 mm which is 9.7% of the observed mean ET. Mean observed ET was 304±65 mm and mean simulated ET was 301±56 mm.

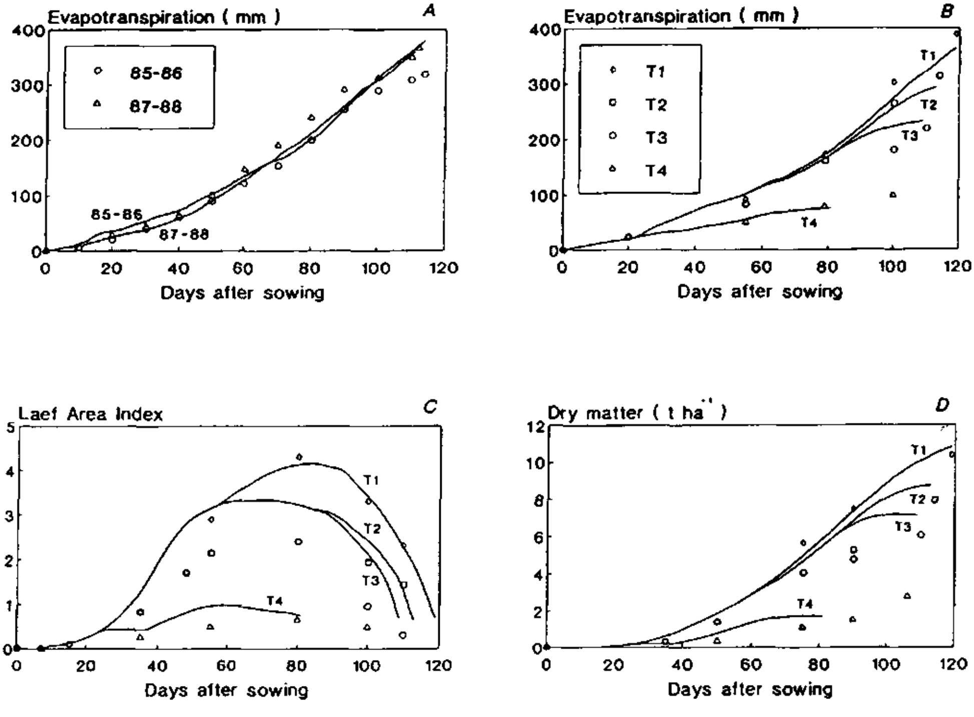

Figure 2.6. Time course of measured (symbols) and simulated (lines) ET for two crop seasons in Experiment 4 (A) and ET (B), *LAI* (C) and dry matter (D) for Experiment 2. In B, C and D, T1 was fully irrigated treatment, T2 and T3 were partially irrigated and T4 was rainfed.

Total N content N content at maturity was available for Experiments 1 and 2 alone. Measured N content at maturity varied from 44 to 170 kg ha^{-1} and simulated N content varied from 20 to 170 g ha^{-1}. The mean observed N uptake was 127 ± 28 kg ha^{-1} and mean simulated total N uptake was 122 $\pm$ 38 kg ha^{-1}. Figure 2.7B shows the scatter of points and 1:1 line. It is evident that for several treatments of both experiments, the model underestimated N uptake slightly while for few treatments of Experiment 1, there was a slight overestimation. The negative value of the intercept and high value of the regression between simulated and measured N content indicate under-prediction of N when N uptake is low and slight over-prediction in treatments with high N application.

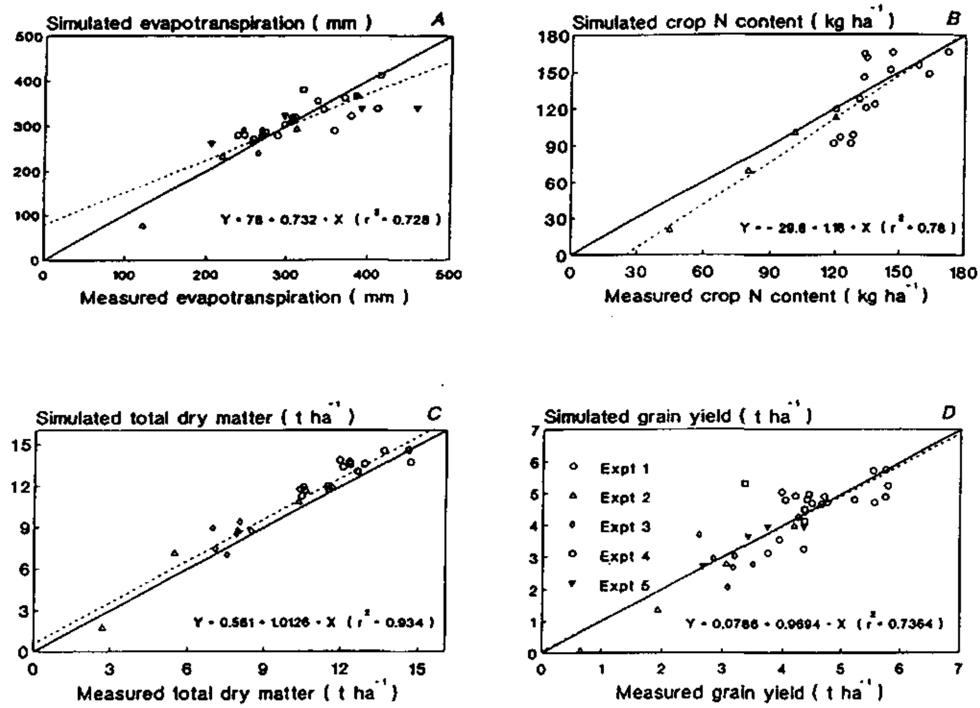

Figure 2.7. Comparison of measured and simulated seasonal ET (A), N uptake (B), total dry matter (C) and grain yield (D) for different experiments. Each point refers to a treatment. (see Table 2.3 for details). Experiment labels for B, C and D are same and shown in Figure 2.6D. Also shown are 1:1 line (solid line), the parameters and line of regression (dashed line) between simulated and observed values.

Leaf area index The time course of change in LAI was simulated for four treatments contrasting in water availability of Experiment 2. In the well-irrigated treatment (T1), simulated LAI was similar to measured LAI at all times (Figure 2.6C). For all other treatments, simulated LAI was always higher than the measured LAI particularly until flowering. During the post-anthesis period, however, the two LAI values were generally close.

Dry matter The dry matter production in irrigated conditions was simulated well as indicated in Figure 2.6D. In treatments with limited water availability, dry matter was close to measured values up to 75 days after sowing. Subsequently, the model slightly over-predicted dry matter. For the severely stressed treatment, the model over-predicted dry matter from 50 days after sowing and until maturity.

Comparison of measured and predicted dry matter at maturity revealed only a slight over-prediction at all levels of stress although there was slight over-prediction (Figure 2.7C). The intercept of the regression was close to zero and slope was 1.01 indicating robustness of the model in explaining crop growth. Standard error of this estimate was 0.79 t ha^{-1} which is 7.7% of the mean observed dry matter. The mean dry matter of simulated and measured treatments was 10.2 ± 2.88 and 10.92 ± 3.02 t ha^{-1}, respectively.

Grain yield Simulated grain yield varied from 0.1 to 5.8 t ha^{-1} and measured yields were between 0.6 and 5.8 t ha^{-1}. The means of two were 4.0 ± 1.2 t ha^{-1} and 3.4 ± 1.3 t ha^{-1}, respectively. Although there was considerable scatter, the simulated yields generally followed the trend of change in measured yields (Figure 2.7D). However, when the yields were above 5.0 t ha^{-1}, the model slightly under-predicted as is also suggested by an evaluation of the statistical parameters. Standard error of the estimate was 0.66 t ha^{-1} which is 16.3% of the observed mean grain yield.

Sensitivity Analysis

The sensitivity of the model to radiation, temperature, available water and N and crop duration in different production environments is illustrated in Table 2.5. The analysis was done by changing the values of the specified inputs by +10%. The simulations were done for New Delhi environment of 1986-87. In potential production environment, yields were sensitive to temperature as well as to TTVG. An increase in temperature and decrease in TTVG reduced yields whereas decrease in temperature and increase in TTVG (more crop duration) resulted in higher yields (Table 2.5). A 10% change in radiation had a negligible effect only. In irrigated production system as well, yields were sensitive to temperature, irrespective of the fertility level, more so when the temperature was increased. The effect of change in WLSTI and NSOILI was significant, particularly when their levels were decreased in low fertility environments. Increase in TTVG resulted in a 5% decrease in grain yield in high fertility, in other cases the response was less than 2%.

In comparison with the above results, rainfed yields increased with increase in temperature. This was largely due to reduced pre-anthesis crop duration which allowed post-anthesis phase to utilize more water although the duration of this phase was also reduced. Reduction in temperature by 10% also increased yield by 2% due to a small increase in grain-filling duration. Since the rainfall during crop season was low, rainfed yields were very sensitive to the values of soil water at sowing time. A decrease in soil N availability increased yields indicating interaction of water and N availability in rainfed environments. That the yields were strongly related to time of anthesis was evident from the response of yield to change in TTVG. Increase in TTVG (reduced crop duration) resulted in earlier anthesis thus enabling the crop to use a greater proportion of soil water in critical grain growth periods.

Table 2.5. Sensitivity of simulated grain yield to change in inputs of ambient temperature, radiation, water (WLSTI) and nitrogen (NSOILI) availability at sowing, and crop duration (TTVG).

Input	% Change in input	% Change from standard yield			
		Potential	Irrigated High Fertility	Irrigated Low Fertility	Rainfed
Standard yield, t ha^{-1}		6.9	5.5	4.2	1.5
Temperature	−10	9.2	3.2	4.5	2.1
	+10	−15.5	−12.9	−14.1	19.0
Radiation	−10	−1.0	1.0	0	23.0
	+10	0.7	−0.6	−3.8	−3.0
WLSTI	−10		−2.4	−6.2	−90.0
	+10		1.1	0	77.0
NSOILI	−10		−1.1	−5.0	15.0
	+10		3.1	0	-1.0
TTVG	−10	5.4	0	−1.0	50.0
	+10	−4.2	−5.0	−1.8	−16.0

Conclusions

The principal objective of developing WTGROWS was to have a management tool to determine climatically determined potential yields as well as to analyse the effect of climatic variables and management of water and nitrogen availability on productivity of wheat in tropical and sub-tropical regions of India. The performance of this model has been evaluated using a large and diverse database assembled from published/unpublished studies conducted by independent workers. In general, model was able to very well simulate the trends in water and nitrogen uptake, dry matter growth and productivity. In particular, the productivity as effected by various climatic constraints and management treatments was satisfactorily simulated. Discrepancies noted in some experiments could be due to inadequate understanding of some processes in the model, uncertainties associated with some parameter values as well as from the use of standard genetic coefficients. The empirical constants used particularly in determining soil N availability may restrict the explanatory power of the model. In addition, the mean observed values may be an inadequate representation of the large variance normally associated with field experiments. In some experiments errors may have resulted in insufficient details for precise initialization of the simulation. Nevertheless, it is clear that the model did not simulate growth and yield well for severe water stress treatments. This should, however, not prevent the use of the model in irrigated and moderate stress environments which are more common in Indian fields. The model results are very sensitive to the prediction of flowering time, therefore, correct simulation of phenology is extremely important in all production systems. We calibrated only a few inputs and yet simulation of plant processes in most studies was reasonable which indicates relative conservatism and feedback relationships in crop behavior. The model results are also very sensitive to correct initialization and weather data. If the model is to serve its purpose of being a useful management tool, it is very essential that a good and precise description of field environment and cultivar is used for initialization of the model along with precise and reliable inputs of weather data.

The model can also be employed for preliminary assessment of impact of climatic change characterized by increasing temperature and carbon dioxide. The major effects of such climatic changes are mediated through the phenological development, canopy photosynthesis and transpiration. These effects are included in the model although the magnitude of their response is yet not well understood.

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3. Uncertainties in crop, soil and weather inputs used in growth models: Implications for simulated outputs and their applications

Abstract

Deterministic crop growth models require several inputs relating to crop/variety, soil physical properties, weather and crop management. The input values used could be significantly uncertain due to random and systematic measurement errors and spatial and temporal variation observed in many of these inputs. Often soil and weather data are approximated using GIS and/or weather generators. In this chapter, total uncertainty in simulated yield, evapotranspiration and crop N uptake has been quantified considering uncertainties in crop, soil and weather inputs. WTGROWS, a crop model that simulates the effect of genotypic, climatic, edaphic and management factors on productivity of spring wheat was used. The uncertainty in each input was represented by a statistical distribution of values based on literature review, actual measurement and subjective expert judgment. The Monte Carlo simulation technique was used to analyse total uncertainty. The analysis showed that uncertainties in crop, soil and weather inputs resulted in uncertainty in simulated grain yield, ET and N uptake which varied depending upon the production environment. Uncertainties in outputs increased as the production system changed from a potential production level to a level where crop growth was constrained by limited availability of water and nitrogen. There was a 80% probability that the bias in the deterministic model outputs was always less than 10% in potential and irrigated production systems. In rainfed environments this bias was larger. The bias in simulated outputs was less than or equal to model error. Most of the uncertainty in outputs caused by variable soil, crop and weather inputs could be represented if the outputs were determined using fixed soil and crop data, and a large series of weather data because weather variability was mainly responsible for variation in yield. In potential and irrigated production systems, inputs relating to crop photosynthesis and leaf area estimation had a large 'uncertainty importance'. Uncertainties in soil N inputs and vapour pressure were also of large importance in irrigated environments. In rainfed environments, uncertainties in soil and weather inputs were dominant and crop parameters had only limited 'uncertainty importance'. The implications of these results in estimates of potential and rainfed productivity, data bases development and in guiding refinement of models are discussed.

Introduction

Techniques of systems analysis and crop growth modelling are increasingly being used in agriculture for estimating production potentials, agrotechnology transfer, designing plant types, strategic and tactical decisions and setting research priorities (Uehera and Tsuji, 1993; Teng and Penning de Vries, 1992; Penning de Vries et al., 1993). Dynamic process based models simulate daily increase in crop growth through a number of processes such as photosynthesis, dry matter partitioning, crop development and transpiration as affected by soil and

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weather factors and crop management. Each of the physiological processes is characterized by certain parameters which are crop/variety specific. The models also require inputs of soil physical properties and climatic factors. The outputs of these deterministic crop models such as grain yield, evapotranspiration and N uptake could be biased due to uncertainties associated with either the model structure and/or the large number of inputs needed for the model. Over the last two decades, crop models have considerably evolved. Their structure is generally considered adequate, although depending upon the assumptions made the results could be uncertain. Such models are a reasonably good approximation of reality and are used for applications after careful calibration and validation in the target environment. Therefore, a major portion of uncertainty in model outputs could be ascribed to incomplete information on input values relating to crop, soil and weather factors, and agronomic management data required to run the model (Burrough, 1989; Richter and Sondgerdth, 1990).

Crop parameter values could be significantly uncertain due to our imperfect knowledge of these caused by random errors related with size and number of observations and systematic errors related with bias in the experimental, measurement, observation and calibration procedures. In addition, many crop input parameters exhibit spatial and temporal variability. Recognizing this, biologists generally report results with standard deviations or standard errors which describe variation associated with the measured variable.

Soil and weather inputs required by the crop models also show spatial and temporal variation and may have considerable measurement errors. These data bases are usually inadequate and are therefore often estimated using Geographical Information Systems and weather generators, respectively (Richardson, 1984; Nix, 1987).

The stochastic nature of many crop parameters and soil and weather input data are expected to result in some uncertainty in the outputs of deterministic crop models. The effect of changes in input values on model outputs (sensitivity analysis) is routinely determined by model developers. Although this is also an important approach to understand input uncertainty effects, it is not sufficient to understand total uncertainties in model outputs. Elston and Glasbey (1991) studied the effect of variation in inputs on weight gain of cattle and found a bias of up to 20% in the deterministic model outputs. Although input uncertainty is important (Dent et al., 1979), it has not received adequate attention in crop growth models and their applications. The objective of this chapter is to quantify total uncertainty in simulated yield, evapotranspiration and crop N uptake considering uncertainties in inputs of crop, soil and weather factors in different production environments characterized by differences in climate and the availability of water and nitrogen. An additional objective is to determine the uncertainty importance of each of the specified inputs. The implications of uncertainties in the model outputs for agricultural decisions are discussed.

Methodology

The crop growth model

To illustrate the effect of input uncertainties, we have used a crop growth simulation model, WTGROWS, that was developed to describe the effect of various climatic factors and their variation, soil characteristics, agronomic management and physiological factors on wheat growth, development, water and nitrogen use in semi- arid tropical and sub-tropical regions (Aggarwal et al., 1994, Chapter 2). The model has been satisfactorily evaluated in key wheat growing regions of India (Aggarwal et al., 1994). It simulates daily dry matter production as determined by radiation intensity and maximum and minimum temperatures and limited by water and nitrogen availability. The model consists of submodels on crop development, growth, photosynthetic area, sink size and grain yield. Soil water and nitrogen balance subroutines determine the availability of water and nitrogen for crop use. The model results are sensitive to weather, agronomic management factors and genotype.

Crop inputs

Each physiological process is characterized by a few important parameters. Thermal time for the period of seedling emergence to anthesis (TTVG) and for the period of anthesis to physiological maturity (TTGF) are variety specific parameters. The model calculates gross canopy assimilation depending upon the gross photosynthesis rate at light saturation (PLMX) and initial light use efficiency. PLMX in turn is estimated from leaf N content which changes with crop age. A fraction of the assimilates is lost in maintenance respiration depending upon the organ and temperature. This fraction for leaves is called RMCLV. The net assimilates are allocated to different plant parts following a development stage dependent partitioning table. The allocation to leaves is determined by the values specified in a table (CAGLV). The leaf area of the crop is calculated depending upon the weight of leaves and specific leaf area (SLA). Root extension rate (ZRTPOT) and maximum rooting depth (ZRTMC) need to be specified for estimating root growth and water uptake.

Grain yield depends on the number of grains formed and the accumulation of dry matter. Grain number is determined by the slope (GNODMA) of the linear relationship between the number of grains and total dry matter at anthesis. The rate of carbon (GFRATE) and nitrogen (NGFR) accumulation in grains depends upon the variety, temperature, and carbohydrates and N available for grain growth. Grain growth is terminated when the crop reaches physiological maturity or the grains achieve their potential weight (POTGWT).

Soil and weather inputs

The soil water and N balance subroutines need input parameter values of maximum soil depth (ZRTMS), water content at field capacity (WCFC) and at wilting point (WCWP), total soil N content (NTOT), urea hydrolysis rate (UHRATE) and fraction of soil N actually available for crop uptake (NUEFF) in various soil layers. The model also needs inputs of soil water (WLSTI) and available N (NSOILI) in the soil at the time of initialization (sowing). The weather variables required to drive the model are maximum and minimum temperatures (TEMP), solar radiation (RADTN), rainfall (RAIN), vapour pressure (VPA) and wind speed (WDSD).

Thus for simulating crop growth the model requires the 12 crop parameters given abbreviations above, 8 inputs to describe soil characteristics and 5 weather variables (Table 3.1). There are other parameters as well but a preliminary sensitivity analysis indicated them to be less important.

Table 3.1. Fixed mean values and probability distributions used for describing uncertainty in the crop, soil and weather inputs. The various inputs and their acronyms are described in the text. Also shown is the maximum percent deviation in the input values from their respective fixed values and the variance (square of s.d.) resulting from the probability distributions. Normal distributions were truncated to determine maximum deviation.

Input	Units	Fixed	Distribution	Maximum deviation, (%)	Variance
Crop inputs					
Phenology					
TTVG	°C days	900	Beta	5.6	2.4
TTGF	°C days	393	Uniform	4.0	3.7
Growth					
PLMX	fraction	1.	Beta	20.0	35.1
RMCLV	kg ha $^{-1}$ day $^{-1}$	0.035	Beta	16.7	129.5
CAGLV	fraction	1.	Uniform	10.0	31.4
SLA	fraction	1.	Uniform	10.0	33.2
Sink strength					
GNODMA	number/g	18	Uniform	20.0	105.3
POTGWT	mg/grain	47	Uniform	10.6	32.9
GFRATE	mg grain $^{-1}$ day $^{-1}$	2.0	Beta	20.0	61.8
NGFR	mg grain $^{-1}$ day $^{-1}$	.04	Beta	33.3	64.5
Root growth					
ZRTPOT	m day $^{-1}$	.03	Beta	33.3	88.4
ZRTMC	m	1.0	Beta	20.0	48.6
Soil inputs					
Soil water characterisitcs					
WCFC(I)	fraction	1.0	Beta	15.0	28.2
WCWP(I)	fraction	1.0	Beta	15.0	20.7
ZRTMS	m	2.0	Normal	10.0	15.7
Soil N characteristics					
NTOT(I)	fraction	1.0	Normal	15.0	68.5
UHRATE	kg ha $^{-1}$ day $^{-1}$	0.25	Normal	13.6	48.5
NUEFF	fraction	0.4	Normal	25.0	68.5
Initial soil characteristics					
WLSTI(I)	fraction	1.0	Beta	10.0	10.7
NSOILI(I)	fraction	1.0	Normal	15.0	85.3
Weather inputs					
Weather variable					
TEMP	°C	0	Uniform	3.1	3.0
RADTN	fraction	1.0	Uniform	10.0	31.0
RAIN	fraction	1.0	Uniform	10.0	28.6
VPA	fraction	1.0	Uniform	10.0	38.4
WDSD	fraction	1.0	Uniform	10.0	31.1

Uncertainty analysis

One way of estimating the effect of uncertainty in crop, soil and weather input parameters is to evaluate the model outputs for all possible combinations of each value of an input with each value of other inputs. The number of combinations however may become enormous for any meaningful computation. For example, if the uncertainty for each of the 25 inputs can be discretized to only 5 levels, the total number of combinations will still be 525. Monte Carlo simulation is an alternative approach where a moderate-sized random sample of all combinations is selected (Morgan and Henrion, 1990). In this approach, the uncertainty in the value of each input parameter is represented by a statistical distribution. A value is drawn at random from the specified distribution for each input. This set of random values (one for each uncertain input) is used in the simulation model to compute the corresponding output values. The entire process is repeated a large number of times (Bouman, 1994). The output values constitute a random sample, the distribution of which can be used to estimate uncertainty in the output due to combined uncertainties in the input. This approach was followed in the present analysis. The randomly generated values for different input parameters had no significant correlation among them. This may not necessarily be true in field. Studies have shown, for example, that the water content at field capacity and wilting point may be correlated (Bouman, 1994).

Uncertainty in input values

Van Heemst (1988) has reviewed the literature for variation in crop input data for use in crop models. Based on this review, other published data, actual measurements, and subjective expert judgment, a statistical distribution was assigned to each of the 25 model inputs (Table 3.1). The ranges of the input values were sufficiently broad to cover variation normally associated with each input. In the present analysis, we have used uniform, beta and normal distributions for describing variation in input values (Table 3.1 and Figure 3.1).

The thermal time for vegetative development (TTVG) varies little for a variety. For a medium duration variety, it varies between 850 and 950 °Cd but the maximum probability is for the values between 880 and 920 °Cd. A beta distribution was used to represent this uncertainty. A fixed value of 900 °Cd was used for describing a medium duration variety (Aggarwal et al., 1994). Relatively much less variation has been reported for thermal time of anthesis to maturity. In general, the values are between 380 and 410 °Cd (Angus et al., 1981; Wiegand and Cuellar, 1981; Saini and Dadwal, 1986). Since in this narrow range it is difficult to specify which values are more likely to occur than others, a uniform distribution was used to describe the variation. A fixed value of 393 °Cd over a base temperature of 7.5°C was used in the present analysis.

Gross photosynthesis rate (PLMX) is calculated in the model from leaf N content. Semi-dwarf varieties show ±20% deviation from the fixed mean values of PLMX (Fischer et al., 1981; Sinha et al., 1981). A bell-shaped beta distribution was used to describe this distribution (Figure 3.1). The maintenance respiration coefficient of leaves (RMCLV) was also described by a beta distribution in the range specified in Table 3.1. The other important inputs in the growth subroutines – CAGLV and SLA – were assumed to show relatively less variation and have a uniform distribution.

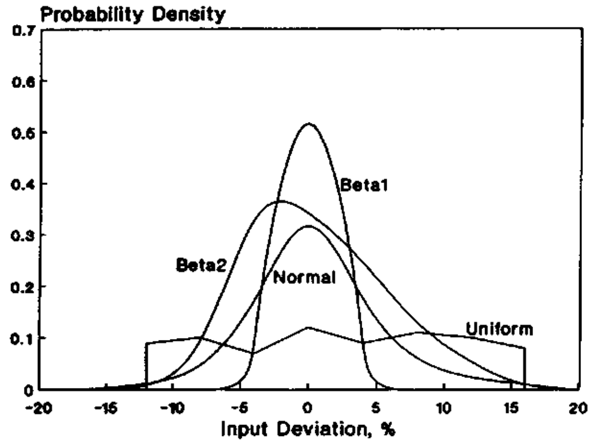

Figure 3.1. Plots of representative beta, uniform and normal probability distributions used for describing uncertainty in some selected inputs. The shape of beta distributions (e.g. Beta1 and Beta2) depends on mean and variance of the input. Acronyms are explained in the text.

The number of grains per unit dry matter (GNODMA) at anthesis varies from 15 to 20 (Fischer, 1985; Aggarwal et al., 1986). Potential grain weight in most wheat varieties varies from 42 to 50 mg grain^{-1} (Fischer and HilleRisLambers, 1978; Aggarwal et al., unpublished observations). Values outside this range are also reported but are not common. A uniform distribution described the variation associated with both GNODMA and POTGWT. A beta distribution was used to illustrate variation in carbon (GFRATE) and N accumulation in grains (NGFR). The maximum root extension rate (ZRTPOT) has been reported to vary widely with variety (Gregory 1989). A beta distribution described the variation in both ZRTPOT and maximum rooting depth (ZRTMC).

Soil water content at field capacity, wilting point and initialization are either measured or extrapolated from soil maps. A range of $\pm$10 to 15% with a beta distribution of values was used to account for the variation in these inputs (Table 3.1). Soil nitrogen shows a large spatial variation within the field. A normal distribution with a large variation is used to describe uncertainty in all soil N inputs.

Weather variables normally have random as well as systematic errors due to measurement and calibration problems. Random errors during the course of simulation of a 100 - 150 day crop with daily time steps are expected to cancel out their effect (Nonhebel, 1993). Therefore, an important reason of uncertainty in these variables is systematic measurement errors. Schaal and Dale (1977) observed that 0.5 to 1 °C bias could be noted in temperature measurements due to time of observation in glass minimum and maximum thermometers. Solar radiation is often indirectly estimated from sunshine hours introducing error in its values. This has been considered in the analysis by allowing a fixed percentage error in the daily measured inputs of radiation, rainfall, wind speed and vapour pressure subject to a maximum of $\pm$10%. This study assumes that maximum uncertainty in maximum and minimum temperatures is limited to ± 0.5 °C. The uncertainties in all weather inputs were assumed to be uniformly distributed.

Monte Carlo simulation

Random values of all inputs were generated from the specified distributions using the program RIGAUS (Bouman and Jansen, 1993). A matrix of 100 combinations was generated from the specified distributions of crop, soil and weather input parameters. The corresponding 100 outputs of grain yield, ET and crop N uptake were calculated by the simulation model. The number was restricted to 100 since comparison of frequency distribution of output (grain yield) in a test run in a rainfed environment showed that there was no significant difference in the results when the analysis was done with 200 combinations. An additional output was generated using fixed values for all input parameters. The uncertainty in input values was quantified as the percent deviation from the fixed value of the input. The uncertainty in output was determined as percent deviation in the output as compared to the deterministic output obtained from the input of fixed values. The deviation (uncertainty) of outputs is plotted as a frequency distribution function.

This analysis was done for a semi- dwarf medium duration variety grown at New Delhi using weather data from three contrasting crop seasons. The crop water requirement is met largely by water stored in the profile and irrigation since rainfall during the crop season is small (average 75 mm). Total rainfall during crop growth period was nil in 1984-85, 70 mm in 1986-87 and 120 mm in 1990-91. Soils at New Delhi are deep sandy loam, and low in soil fertility.

Grain yields were determined at three levels of production environments:

- Potential production environment: assuming no effect of water and nutrient stresses on crop growth. Growth is limited only by major crop characteristics and ambient temperature and radiation. A switch in the model prevents any effect of water and/or N stress on potential growth. Thus crop parameters relating to root growth and N balance and all soil inputs are not relevant.
- Irrigated production environment: assuming application of 120 (80+40) kg ha^{-1} N and five irrigations (total 300 mm) during crop season. Water and N availability occasionally limit crop growth. All crop, soil and weather inputs are considered in this analysis.
- Rainfed production environment: assuming no irrigation and 40 kg ha^{-1} basal N application. Water and N stresses limit crop growth for a large period. All crop, soil and weather inputs are considered.

Monte Carlo simulation was carried out for two scenarios of uncertainty in each production environment:

a) uncertainty in only crop parameters. Soil and weather parameters were maintained at their fixed values.

b) uncertainty in all crop, soil and weather input parameters specified in Table 3.1.

Uncertainty importance of various inputs

To determine the relative contribution of uncertainties in crop, soil and weather factors on uncertainty in grain yield, a step wise linear regression was developed between percent deviation in yield (uncertainty in dependent variable) and percent deviation in different inputs (uncertainties in independent variables). A maximum of 15 significant independent variables were allowed in the regression. Normalizing dependent as well as independent variables with respect to their 'fixed' values helped in overcoming interpretation problems due to differences in units and/or scale of measurement of each variable.

The linear model was:

$$y = b_0 + \sum_{j=1}^{n} b_j x_j \tag{3.1}$$

where y is the percent deviation in output relative to the deterministic output, n is the number of inputs and index j refers to various inputs. The partial regression coefficient, bj of the linear model provides a measure of linear sensitivity of output y to inputs xj when all other inputs are held at their mean value. The slope alone as a measure of uncertainty importance, however, has a drawback because it ignores the degree of uncertainty in each input. Because x variables are independent, uncertainty importance of each input can be determined as the product of its partial regression coefficient and variance. The total uncertainty in output expressed as variance [Var (y)] is explicitly decomposed as the sum of the contribution from each input ($[dy/dx]^2$ var (x)).

$$\mathrm{Var}\,[y] = ([dy/dx_1]^2\,\mathrm{var}\,(x_1)) + ([dy/dx_2]^2\,\mathrm{var}\,(x_2)) + ([dy/dx_n]^2\,\mathrm{var}\,(x_n)) \tag{3.2}$$

The uncertainty importance of different inputs in estimating grain yield was determined using averaged values of grain yields over three years of analysis.

Results and Discussion

Uncertainty in potential grain yield

Uncertainties in crop parameters resulted in variation in simulated potential grain yield. Cropping season had a significant effect on this variation (Table 3.2). The predicted grain yields deviated between –24.3 and +10.8% of the deterministic yields estimated by fixed values of inputs. Relatively the deviation was very high in 1986-87. In the other two years, the deviation was within ±11% of the deterministic yield. The frequency distribution of pooled results showed that in 47% cases the uncertainty in yields was between –2.5 to +2.5% only. There was a 89% probability of yields being within 9% of the deterministic yield (Figure 3.2). The mean, median and modal values were close to zero except in 1986-87 when the mean was –3.4% and the median value was –5%.

Considerations of systematic errors in weather inputs had only a small impact (soil inputs are not relevant in this production system). The grain yields deviated between –16.6 to 12.9% of the deterministic yield depending upon the year (Table 3.2). There was a large probability of yield being equal to or lower than the deterministic yield (Figure 3.2). There was a 87% probability that yields were biased by less than ±7.5% only. The frequency distribution analysis showed that the median and modal values were zero in 1984-85 and 1990-91 but −5% in 1986-87.

Table 3.2. Effect of uncertainties in a) crop parameters alone and b) in all inputs on uncertainty in grain yield in different crop seasons and production environments.

Crop season	Uncertainty in grain yield, % deviation from deterministic yield					
Uncertainty in crop parameters alone						
Potential production environment						
	Minimum	Maximum	Standard deviation	Mean	Median	Mode
84-85	−7.55	10.83	3.44	1.04	0	0
86-87	−24.30	7.80	6.92	−3.42	−5.0	0
90-91	−9.17	9.08	3.43	0.74	0	0
Pooled	−24.30	10.83	5.35	−0.55	0	0
Irrigated production environment						
84-85	−7.56	4.17	2.28	−0.58	0	0
86-87	−4.87	8.15	2.66	0.88	0	0
90-91	−7.24	5.47	2.38	−0.31	0	0
Pooled	−7.56	8.15	2.52	0	0	0
Rainfed production environment						
84-85	−54.3	38.55	16.45	−3.36	0	10
86-87	−59.1	31.6	17.17	0.97	0	−60,0
90-91	−8.4	9.5	3.40	−0.32	0	0
Pooled	−59.1	38.55	13.96	−0.91	0	0
Uncertainty in all inputs						
Potential production environment						
84-85	−8.41	12.91	4.57	2.54	0	0
86-87	−16.67	14.33	6.11	−0.34	−5	−5
90-91	−8.4	9.5	4.45	2.33	0	0
Pooled	−16.67	12.91	5.17	1.11	0	0
Irrigated production environment						
84-85	−16.67	14.33	6.11	−0.34	−5	−5
86-87	−12.11	8.28	4.23	−0.35	0	0
90-91	−11.65	9.11	4.16	−0.59	−5	0
Pooled	−16.67	14.33	4.91	−0.43	−5	0
Rainfed production environment						
84-85	−100	111.97	40.31	−1.77	0	10
86-87	−100	90.4	46.91	−4.11	0	−60,0
90-91	−26.83	11.45	6.88	−4.47	0	0
Pooled	−100	111.97	35.9	−3.46	−10	0

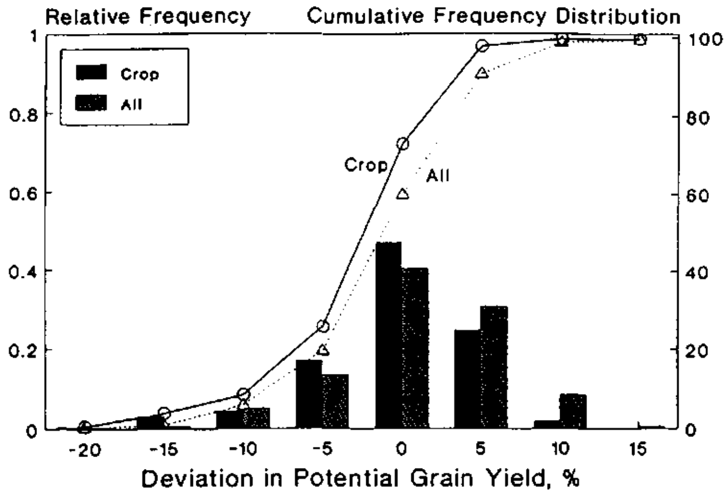

Figure 3.2. Effect of uncertainties in 1) crop parameters alone and 2) in all inputs specified in Table 3.1 on uncertainty in simulated potential grain yield. Uncertainty in later refers to percent change relative to potential yield simulated in that year with fixed values of inputs. Distributions are based on pooled results of three crop seasons. Boxes represent frequency density and lines are cumulative frequency distributions. Each value on x-axis is the mid-point of a frequency distribution where interval width was 5%.

Uncertainty in irrigated grain yield

In the simulated irrigated production system, the effect of cropping season on uncertainties in grain yield were small particularly when uncertainties in crop parameters alone were considered (Table 3.2). Depending upon the year, the deviation from deterministic yield was 4 to 8% when only crop parameters were considered, and between 8.3 and 16.7% when all inputs were uncertain. If only crop parameters were uncertain, there was a 69% probability that yields deviated less than 2.5% from the deterministic yields (Figure 3.3). That the yields deviated less than 7.5% from deterministic yields had a probability of 99% and 89%, respectively when uncertainties were in crop parameters and in all inputs. Mean, mode and median values of grain yield were always within 95% of deterministic grain yields (Table 3.2).

Uncertainty in rainfed grain yield

The bias in estimated grain yield increased significantly in this environment and the cropping season had a strong effect on its magnitude. When uncertainties in crop parameters alone were considered, deviation from deterministic grain yields was large in the dry environment of 1984-85 and small in 1990-91 when there was sufficient rainfall. However, irrespective of the season there was a 56% probability that this deviation was less than 5%, and a 87% probability that this deviation was less than 15% (Figure 3.4). The mean and median values were nearly zero. Due to large differences in yields in different years the modal values varied from zero to –6.0% (Table 3.2). When all inputs were uncertain, the deviation in grain yield was between –100 to +112% of the deterministic grain yield (Table 3.2). The deviation was relatively smaller (+27%) in the wet year (90-91) than other two years. There was a 48% probability that the deviation of deterministic grain yield was less than 15%. That the grain yield were between 25 and 85% of the deterministic yield had a cumulative probability of 23% (Figure 3.4). There was also a 14% probability of yields being 15 to 55% greater than that estimated by fixed inputs.

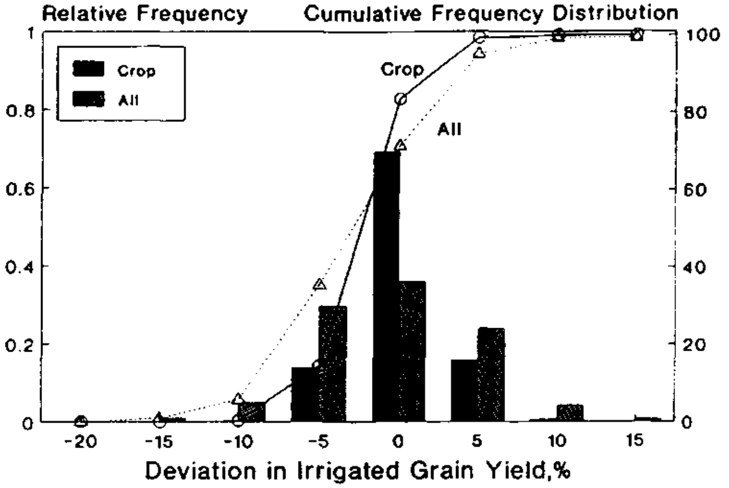

Figure 3.3. Effect of uncertainties in 1) crop parameters alone and 2) in all inputs specified in Table 3.1 on uncertainty in simulated irrigated grain yield. Uncertainty in later refers to percent change relative to irrigated yield simulated in that year with fixed values of inputs. Distributions are based on pooled results of three crop seasons. Each value on x-axis is the mid-point of a frequency distribution where interval width was 5%.

Uncertainties in ET and crop N uptake

The effect of uncertainties in different inputs on the bias in estimation of ET and crop N uptake was determined for all three crop seasons for irrigated and rainfed production environments. Figure 3.5 shows the probability distribution for the pooled results. When only crop parameters were considered, uncertainties in ET and N uptake in irrigated as well as rainfed environments were very small (Figure 3.5). Percent deviation in ET and N uptake from their relative deterministic values varied between –5 to +5% in irrigated environments and –21 to +3% in rainfed environments. Irrespective of the environment, there was only a 5-6% probability that the deviation in ET was greater than 2.5%. That the deviation in N uptake was less than 2.5% had a 95% probability in irrigated environments and a 83% probability in rainfed environments.

Inclusion of uncertainties in soil and weather inputs in the analysis increased the uncertainties in the estimation of ET as well as N uptake (Figure 3.5). In both these outputs, the deviation from the deterministic values varied between –17 to +19% in irrigated environments and between –100 to +112% in rainfed environments. There was however, a 78-81% probability that the bias in ET and crop N uptake was less than 7.5% in irrigated environments. In rainfed environments as well, there was a 73% and 49% probability, respectively that the bias in ET and N uptake was less than 7.5%.

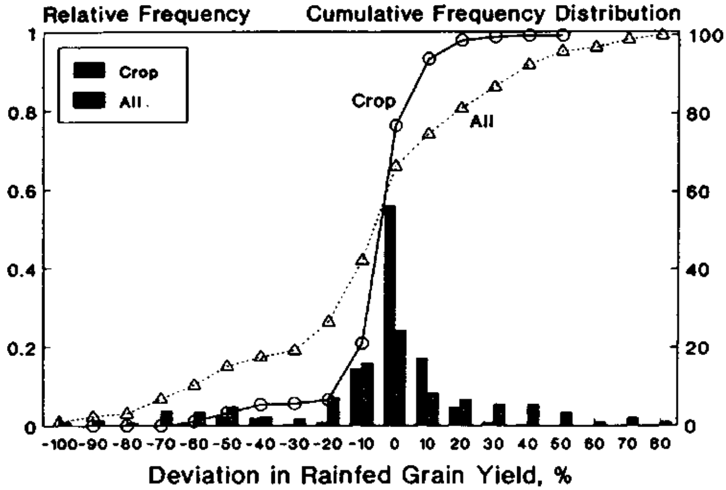

Figure 3.4. Effect of uncertainties in 1) crop parameters alone and 2) in all inputs specified in Table 3.1 on uncertainty in simulated rainfed grain yield. Uncertainty in later refers to percent change relative to rainfed yield simulated in that year with fixed values of inputs. Distributions are based on pooled results of three crop seasons. Each value on x-axis is the mid-point of a frequency distribution where interval width was 10%.

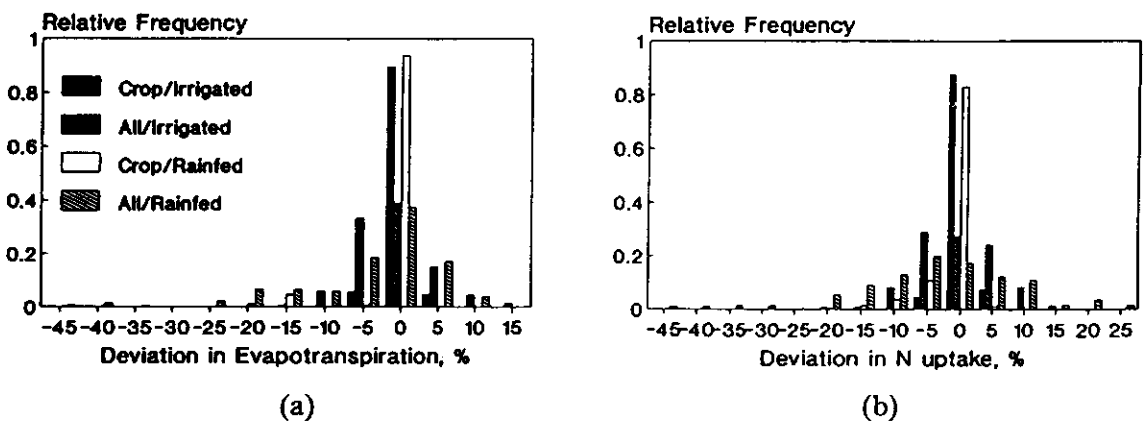

Figure 3.5. Effect of uncertainties in 1) crop parameters alone and 2) in all inputs specified in Table 3.1 on uncertainty in (A) evapotranspiration and (B) crop N uptake in irrigated and rainfed production systems. Uncertainties in outputs refer to percent change relative to simulated output in that season with fixed values of all inputs. Each value on x-axis is the mid-point of a frequency distribution where interval width was 5%.

The above results indicate that deterministic estimation of grain yield, evapotranspiration and N uptake, the major outputs of crop simulation models, could be biased unless uncertainties in crop, soil and weather inputs are considered. The magnitude of this bias varies with the production environment and the simulated output parameter. Relatively uncertainties in outputs increase as the production system changes from a potential production level to a level where crop growth was constrained by limited availability of water and nitrogen. It can be summarized from the present uncertainty analysis that there is a 80% probability that the bias in model outputs in potential and irrigated production systems was always less than 10%. Even in rainfed environments there was a 48% probability that the bias was less than 15%. The random distributions of input values as generated in the present study and the dynamic interaction and compensation among plant processes result in relatively small deviations from deterministic values of outputs. This bias in grain yield, ET and crop N uptake due to uncertainties in inputs is generally less than or equal to model error (standard error of estimate of a linear regression between simulated and real system values). For WTGROWS, the model used in this study, this error was observed to vary between 9 to 16% depending upon the output and production environment (Aggarwal et al., 1994).

Climatic variability is often considered in many applications of crop models. This is accomplished by running the simulation model with fixed crop and soil inputs and daily real time or generated weather data for a large number of years. This exercise thus considers uncertainty in mean weather data and results in a series of outputs where probability distributions are then used to evaluate risk aversion options. To determine if such an analysis would include the variance in output values caused by the uncertainties in crop, soil and weather inputs, grain yield, ET and N uptake were simulated using fixed values of all inputs and 17 years of actual daily weather data. The analysis was restricted to only 17 years since no more weather data was available. Summary statistics of the simulated frequency distribution are presented in Table 3.3. These are compared with the earlier described pooled results of uncertainty analysis done with limited weather data and uncertain inputs. The results showed that in general, all outputs of uncertainty analysis varied over a much larger range particularly towards lower end than that determined using fixed values of all inputs. This resulted in higher standard deviation and slightly lower mean and median output values in case of uncertainty analysis. If extreme output values of uncertainty analysis are left out of the frequency distribution, it is likely that the two approaches will result in similar output distributions. The deviation in results of two approaches could also be due to limited number of observations (n=17) in the analysis using fixed values as against 300 observations in uncertainty analysis. Nevertheless, it is clear that in potential and irrigated production environments, most of the uncertainty in grain yield, ET and crop N uptake caused by input uncertainties is included in the variation estimated by simulations using fixed model inputs and a large series of weather data. In rainfed environment, input uncertainties have a large effect.

Often it is desired to know the best estimates of yield, ET and other similar outputs, for example, for agricultural zonation. This analysis has shown that since the uncertain outputs are generally symmetric around the mean (most outputs were near normal in distribution as evident from Figures 3.2 –3.4), fixed values of inputs can provide that estimate with a high probability particularly in relatively constraint free environments. But if one is performing an analysis where risk is likely to be important, for example strategic and tactical decisions about irrigation and fertilizer application, it is important to consider input uncertainties. Expending resources on acquiring additional information on soil and weather data will be valuable. Procedures to reduce parameter uncertainty as suggested by Klepper and Rouse (1991) may also be useful.

Table 3.3. Frequency distribution parameters of grain yield (GY, t ha^{-1}), evapotranspiration (ET, mm) and crop N uptake (N, kg ha^{-1}) as determined by using fixed values of crop and soil inputs and 17 years of actual weather data. For comparison, the frequency distribution parameters of uncertainty analysis with uncertainties in all inputs are also shown.

Inputs	Outputs						
	Name	Minimum	Maximum	Mean	SD	Median	Mode
Potential production system							
Fixed	GY	5.3	8.0	6.7	0.6	6.7	6.8
Uncertain	GY	5.0	8.0	6.2	0.7	6.3	6.7
Irrigated production system							
Fixed	GY	4.4	6.3	5.4	0.4	5.4	5.5
Uncertain	GY	3.7	5.9	5.1	0.5	5.2	5.3
Fixed	ET	314	465	374	42	368	365
Uncertain	ET	269	468	369	49	370	430
Fixed	N	120	129	126	2	126	128
Uncertain	N	99	143	123	8	123	123
Rainfed production system							
Fixed	GY	0.8	4.8	2.4	1.1	2.5	1.0,3.0
Uncertain	GY	0	5.3	2.4	1.6	1.6	1.0,4.4
Fixed	ET	206	281	245	20	242	245
Uncertain	ET	77	298	226	36	234	250
Fixed	N	53	84	75	9	77	80
Uncertain	N	21	107	69	16	78	78

Relative uncertainty importance of various inputs

Potential production environment When uncertainties in crop inputs alone were considered, 86% of the uncertainty in grain yield could be explained by linear regression (Table 3.4). The first variable to enter the regression was PLMX, the key parameter in determining dry matter production, and it also had the largest uncertainty importance. Grain yield was also very sensitive to value of SLA, its uncertainty importance was 21% indicating that correct estimation of LAI is very important in simulating potential yields. GNODMA also had a reasonable uncertainty importance because of large variance associated with its input value

(Table 3.1). Other crop inputs contributed little to variation in grain yields. The uncertainty importance of phenological parameters was low due to their small variance relative to other inputs (Table 3.1) although they had a strong effect on grain yield (regression coefficients between TTVG and grain yield and TTGF and yield were −0.497 and 0.495, respectively). Inclusion of the entire variation in TTVG found in wheat varieties of different durations (increased variance) would significantly alter the uncertainty importance of various inputs.

When uncertainties in weather variables were also considered the results showed that 85.6% of the variance in grain yield could be explained by the regression. The major reason of uncertainty in yield was due to crop inputs (79.8% of the total) and only a small portion of total uncertainty was due to errors in estimation of temperature and solar radiation (Table 3.4). Gross photosynthesis rate retained its number one position in importance followed by SLA and GNODMA. Although temperature had a significant negative effect and radiation a positive effect on grain yield (regression coefficients between TEMP and yield and RADTN and yield were −0.389 and 0.160, respectively), small systematic errors of 0.5°C in temperature measurement and 10% in estimation of solar radiation had only a limited significance on simulated potential yield.

Irrigated production environment The linear regression explained 91.5% of the total uncertainty in irrigated grain yield due to uncertainties in crop parameters (Table 3.4). PLMX, SLA and TTVG had the largest uncertainty importance. TTGF, RMCLV and CAGLV were also significant but had little influence on grain yield. All parameters related to post-anthesis sink strength as well as root growth were not of any significant uncertainty importance.

Consideration of uncertainties in soil and weather inputs together with crop input parameters explained 93.4% of the total variance in grain yield. Only 39.9% was explained by crop parameters (Table 3.4). PLMX and SLA were the only crop parameters with a large uncertainty importance. Soil factors together contributed 40.9% in total yield variance. Availability of soil N for crop uptake (NSOILI + NUEFF) explained 30.4% uncertainty in grain yield and thus had the largest uncertainty importance among soil inputs. Total N content in the soil and urea hydrolysis rate had almost no uncertainty importance. The uncertainty in soil water content at field capacity (WCFC) and at wilting point (WCWP) had a negligible role in explaining variance in grain yield. However, soil water at sowing time (WLSTI) had a reasonable importance (Table 3.4) probably because the crop had to grow on stored soil water for the first 21 days after sowing (first irrigation was applied 22 days after sowing). During this period, greater stress is likely to reduce expansion of roots in deeper layers and thus effect water uptake and yield.

Systematic errors in weather inputs resulted in 11.4% variance in grain yield. The major share was of vapour pressure which was important in determining evapotranspiration. Radiation and wind speed had a small effect but temperatures and rainfall were of no uncertainty importance (Table 3.4).

Table 3.4. Uncertainty importance of crop, soil and weather inputs in total uncertainty in grain yields in different production environments. Larger the value the larger is the uncertainty importance of that input. Values are shown for only significant inputs and have been normalized for the total variance explained by the regression model (Equation 2). Two scenarios are considered: uncertainties in crop inputs alone and uncertainties in all inputs.

Input	Uncertainty importance					
	Crop parameters alone			All inputs		
	Potential	Irrigated	Rainfed	Potential	Irrigated	Rainfed
Crop inputs						
Phenology						
TTVG	2.6	11.4	13.1	2.6	2.3	0.8
TTGF	4.1	6.3	-	4.5	4.3	-
Growth						
PLMX	38.7	50.9	-	35.5	24.3	-
RMCLV	2.6	3.4	-	2.8	1.0	-
CAGLV	2.1	2.1	-	3.3	1.0	-
SLA	21.0	16.7	2.7	22.2	7.0	-
Sink strength						
GNODMA	11	.2	-	7.7	-	-
POTGWT	4.1	-	-	1.3	-	0.6
GFRATE	-	-	-	-	-	-
NGFR		0.2	-		-	-
Root growth						
ZRTPOT		0.4	2.2		-	0.6
ZRTMC		-	-		-	-
Weather inputs						
TEMP				2.1	-	1.6
RADTN				3.7	3.5	7.2
RAIN					-	-
VPA					7.9	27.4
WDSD					1.2	1.9
Soil inputs						
Soil water characteristics						
WCFC(I)					2.9	1.0
WCWP(I)					0.3	4.1
ZRTMS					-	-
Soil N characteristics						
NTOT(I)					1.6	-
UHRATE					-	-
NUEFF					16.8	6.4
Initial soil characterization						
WLSTI(I)					7.3	27.5
NSOILI(I)					12.0	2.9
% Variance explained by all	85.9	91.5	18.0	85.6	93.4	81.9

Rainfed production environment When uncertainties in crop parameters alone were considered, only three parameters (TTVG, SLA and ZRTPOT) were significantly related to grain yield but these were able to explain only 18.0% of the total uncertainty (Table 3.4). The largest share (13.1%) was of TTVG confirming the well known role of crop duration in escaping drought. But for SLA, all other parameters related to growth and sink strength had no uncertainty importance. Maximum rooting depth also was not important. Obviously, the dynamic interactions among crop parameters and various crop physiological and soil processes are of great importance in such constraint environments.

Inclusion of soil and weather inputs in the analysis explained 93.4% of the total uncertainty in simulated rainfed yields. In this scenario, crop parameters had almost no importance in explaining uncertainty in grain yield although the later was very large (Figure 3.4). The soil input parameters alone explained 55.4% of the total variance, rest was due to uncertainties in weather variables (Table 3.4). Since the seasonal rainfall is very low (50 - 100mm), rainfed wheat in India is largely dependent on residual soil water. Therefore, amongst soil inputs, moisture content at sowing time (WLSTI) had the largest uncertainty importance.

Uncertainties in WCFC and WCWP had very low value. Similarly NTOT, UHRATE and ZRTMS had no uncertainty importance. Vapour pressure and radiation were the weather inputs that explained 34.6% of the variance in grain yield.

It can be concluded that as the probability of water and nitrogen stresses increases, uncertainties in soil and weather inputs become so dominant that most crop input parameters lose their uncertainty importance. Even amongst soil inputs, precise estimation of only a few was important. Many of the inputs with small uncertainty importance such as WCFC, WCWP, ZRTMS and NTOT are often approximated or interpolated from maps. No serious error will be committed in simulation so long as errors in their estimation are within the ranges used in this study, at least in New Delhi type environments. Soil water and N content at initialization had large uncertainty importance. Therefore, all efforts must be made to increase precision in their measurements. Similarly, vapour pressure and radiation amongst weather factors had large uncertainty importance. Care should be taken in their measurement as well.

These results for uncertainty importance have few important implications for simulation model development and their practical applications. Estimates of potential and irrigated wheat yields made earlier with WTGROWS (Aggarwal and Penning de Vries, 1989; Aggarwal, 1991, 1993) and in other studies (Van Lanen et al., 1992) having a similar range of uncertainties have a large probability of representing the true average value; the uncertainty being very small (zero to 7.5% only) (Figures 3.2 and 3.3). By comparison, estimates of rainfed productivity could be fairly uncertain since soil and weather inputs for several locations were interpolated from maps which introduced uncertainty in input values. However, there is a large probability that these yields deviated by less than 15% only (Figure 3.4). There is a need to build sufficiently detailed and accurate databases for estimating input values of soil and weather characteristics.

Uncertainty analysis can also be useful to guide refinement of existing models as well as in developing new, more appropriate models depending upon the objectives. If the simulation objective is to determine production potential of a crop/variety the photosynthesis routines should be sufficiently detailed and its parameters be measured with due care. Accuracy required in physiological processes such as photosynthesis can be relatively lower if the model goal is to assist in making strategic and tactical decisions in a variable soil water/N environment. Fixed values of crop parameters will not introduce large biases. Here, greater attention should be paid on reducing uncertainties associated with measurement of soil and weather inputs.

The results presented in this chapter are specific to the range of uncertainties used in the inputs, nature of inputs, model structure and to the environments similar to that of New Delhi. Non-linear responses of the inputs and interactions among them were not taken into account while determining uncertainty importance. Although much of the results will be true, at least qualitatively, in most other analyses as well, care needs to be exercised in extrapolating. The approach, however, can be considered as a framework to consider uncertainties in model inputs and their effects on simulation outputs.

Conclusions

Outputs of crop growth models may be uncertain depending upon the range of variation/uncertainty in crop, soil and weather input parameters and production environment. Yet crop models will remain important in applications related to estimating production potentials, strategic and tactical decisions and agrotechnology transfer since these are an efficient, quantitative tools to integrate complex dynamic interactions of crops/genotype with climatic, edaphic and agronomic environment. The conclusions derived from conventional field experiments as well have uncertainty in view of the spatial variability and other random and systematic errors considered in this study. In addition, it may be extremely difficult to design and conduct field experiments to simultaneously investigate the effect of variations in crop, soil and weather factors. The bias in simulated yield, ET and N uptake due to uncertainties in inputs are small and generally within the model error in low or no constraint environments. Using fixed values of crop and soil inputs and a long series of weather data can provide an alternative to represent variance in simulated outputs. In water and N limited environments, deterministic model outputs often have a large bias. There is a clear need to reduce uncertainties in our measurements particularly related to soil characteristics. Detailed and accurate databases need to be developed for major inputs of crop models.

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4. Analysing the limitations set by climatic factors, genotype, and water and nitrogen availability on productivity of wheat. II. Climatically determined potential yields and optimal management strategies

Abstract

The objectives of this chapter are to establish the climatically determined potential grain yields of wheat for different regions of India, to quantify the gap between actual and potential yields and to determine the optimal levels of irrigation and N required for given productivity levels. The analysis is based on simulations made with the crop growth model WTGROWS. Simulated potential grain yields, determined by solar radiation and temperature, varied between 2.56 and 8.25 t ha^{-1} for 138 locations spread all over India. In general, yields increased with latitude and inland locations had higher yields than the coastal locations at the same latitude. These trends were related to mean temperature differences over latitude/location. The results indicate a strong linear decline in grain yield as mean temperature increased. Late sowings had smaller yields as well as increased variability in yield. The amount that decreased for each day's delay in sowing was more when potential yield was high. The yield gap was at least 2 t ha^{-1} irrespective of location and a significant portion of this was due to delayed sowing.

Crop simulation with different amounts of nitrogen and irrigation showed significant interaction between water and N availability and climatic variability, particularly with low inputs. Optimal N application varied with the amount of water available. Yield variance of stressed wheat crops is moderated strongly by irrigation but low levels of N fertilizer application may modify the response.

Introduction

In India wheat is grown in tropical and sub-tropical climates. The total production of wheat in the country in 1965 was 12.3 Mt. Since then, with the introduction of semi-dwarf cultivars and expanded use of irrigation and fertilizers, production has increased impressively to 56 Mt in 1992. This was largely due to increase in productivity per unit area. At present, mean productivity of wheat in farmers fields ranges from 0.65 t ha^{-1} to 4.5 t ha^{-1} depending upon the region. In most agro-climatic regions, particularly in north-western India, there has been no significant increase in experimental wheat yields during the last two decades (Sinha, 1999). On the other hand, demand for wheat and other cereals is increasing rapidly. It is

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therefore important to know if the trend for increasing wheat yields will continue and for how long.

The production potential of a site is largely determined by its climatic, edaphic and crop properties and their interactions. Crop simulation models deal with interactions of crop growth with climatic factors, soil characteristics, and agronomic management, and therefore can be used to estimate climatic limitations to growth and yield. In Chapter 2, we have described a wheat model, WTGROWS, that simulates the effects of these factors on growth, development, water and N use, and yield. In well fertilized and irrigated plots where abiotic and biotic stresses are non-limiting, crop productivity is determined largely by interactions of crop growth and development with solar radiation and temperature. The first objective of this chapter is to establish this climatically determined potential grain yield for different locations in India where wheat is currently produced. The effect of climatic variability on potential yield is also considered for a few contrasting locations. The second objective is to quantify the magnitude of the yield gap between potential and actual yields at different sites.

Because wheat in India is grown in the post-rainy season and on soils poor in fertility, it is essential to apply irrigation and fertilizers. Increase in productivity of wheat during last three decades was due to availability of new high-yielding cultivars as well as to higher inputs, particularly of irrigation and nitrogen. Today more than 70% of the wheat area is irrigated although it does not necessarily mean that the entire area receives optimal amount of irrigation (WPD, 1989). Consumption of fertilizers has also increased; fertilizer use in various regions varies from 5 kg ha^{-1} to 160 kg ha^{-1} (WPD, 1989). Further increase in yield would obviously require higher N uptake and water use. Because application of more inputs may not always be economical, it is necessary to optimize their use efficiencies by improved management practices based on in-depth science.

A large number of experiments have been done on effects of irrigation and/or water on productivity of wheat (Van Keulen, 1983; French and Schultz, 1984; Gajri et al., 1993). Multiple regression models have been developed to determine irrigation and N fertilizer requirements of crops (Kroentazer and Berliner, 1988; Gajri et al., 1993). However, the magnitude of response to inputs may vary in different locations/ experiments/ years because of inadequate consideration of interactions with genotype, climatic factors and their variability, and agronomic management. Crop growth models, by integrating the effects of different factors on productivity, provide a unique opportunity to supplement results of field trials. Such models have been used for evaluating the interaction effects of fertility, planting dates, soil type and climatic variability on maize productivity in Malawi (Singh et al., 1993) and in Kenya (Keating et al., 1993). An additional objective of this study was to evaluate the effect of various levels of irrigation and nitrogen fertilizer application at different stages on crop productivity and to determine their optimal level for a given productivity level. Such an analysis requires detailed databases on daily weather, soil profile characteristics in terms of water and nitrogen availability and accurate initialization of management practices. This analysis has been done for New Delhi, a typical wheat growing environment of India.

Materials and Methods

The Model

The analysis in this chapter is based on simulations made with crop growth model, WTGROWS (Chapter 2, Aggarwal et al., 1994). It simulates daily dry matter production as a function of radiation intensity and maximum and minimum temperatures, and water and nutrient stresses. By use of appropriate switches to eliminate the effects of water and nitrogen stress on crop growth, climatically potential grain yields can be determined.

The model requires daily inputs of maximum and minimum temperatures and solar radiation as the driving variables. The monthly climatic averages for 138 locations below 600 m elevation from all wheat-producing regions of India constituted the basic database. Sites above 600 m elevation were not included in the analysis because there is limited cultivation in these areas and the model was not evaluated at such locations. Daily values were obtained by linear interpolation. Because wheat is grown in clear sunny weather in almost all parts of India, simulated potential yields obtained from the interpolated daily values (from monthly means) were only marginally different from those obtained by using several years of measured daily values (results not shown). The extent of climatic variation in these sites is represented by the lower and upper limits of climatic factors for the month of January as follows:

Maximum temperature	18.5 to 32.2 °C
Minimum temperature	4.4 to 20.3 °C
Solar radiation	12.4 to 25.4 MJ m^{-2} day^{-1}

For determining year- to year- variability in grain yields, historic daily weather data for several years are needed. Appropriate locations representing major wheat-producing regions were selected: Delhi (28°N, 77°E), Kota (25°N, 75°E), Pusa (25°N, 85°E), Indore (22°N, 75°E), and Solapur (17°N, 76°E). Daily weather data for 10 to 20 years was made available by Indian Agricultural Research Institute, New Delhi, India Meteorological Department, Pune and Central Research Institute for Dryland Agriculture, Hyderabad.

To analyse the effect of irrigation and nitrogen application on productivity, simulations were done for wheat grown in New Delhi. For that additional daily weather data required were rainfall, wind speed and vapour pressure. The model requires information on the soils particularly in relation to water holding capacity. The soils at New Delhi are Typic Ustochrepts (UDSA Soil Taxonomy), sandy loam, and about 150 cm deep. A representative water retention profile was used.

Simulation

Climatically determined potential grain yields - Potential grain yields were estimated for a 'standard' medium duration cultivar for each of the 138 locations for three sowing dates (1, 7 and 15 November). The genotypic constants were those specified by Aggarwal et al. (1994). The maximum yield obtained in any of these sowings was considered potential yield of that location.

An important aspect in evaluating the suitability of a crop is the stability of performance over years. Wherever historic weather data for several years are available, year-to-year variation in grain yields can be simulated. Frequency distribution analysis of this data set provides the probability of obtaining a given grain yield as well as the impact of climate on vulnerability of productivity of a cultivar. Difference between 75 and 25% probability levels is used here to indicate the extent of effect of climatic variation; the larger the difference the larger is the yield variance due to climate. Because potential yield varies significantly with location, this variance is redefined on a relative basis:

$$\text{Yield Variance Index (YVI)} = \frac{\text{Yield at 75\% probability} - \text{Yield at 25\% probability}}{\text{Yield at 50\% probability}}$$

This analysis was done with a 15 November sowing date for locations mentioned earlier.

A large proportion of wheat is sown much later than the optimal time (WPD, 1989). To study the effect of late sowing, simulations were conducted for all 138 locations with sowing on 1 January. The loss in grain yield due to late sowing was determined by estimating reduction in grain yield per day if sowing is delayed from November 15 to January 1. Analysis with different sowing dates showed that in this period there is a linear decrease in grain yield with delay in sowing at most locations (data is not shown).

The effect of climatic variability on optimal sowing date was estimated for New Delhi for a medium duration cultivar. This was simulated using daily values of weather for last 20 years. The simulations were made for crops sown at 15-day intervals starting 1 November until 1 January. At many locations short duration cultivars yield higher in late sowings (Gill, 1979), therefore, an additional simulation run was made with early maturing cultivars. It was assumed that the major primary difference in cultivars is in their flowering behavior. To mimic this response, thermal time required for seedling emergence to flowering was reduced by 150 degree-days for January sowings.

Yield gap Mean grain yields obtained by farmers on a regional basis are reported every year by Government of India (e.g. Anonymous, 1990). The smallest reporting unit is a district. Records of actual yields obtained by farmers for smaller regions such as village are not available. It was assumed that the mean district yield is the actual yield of all locations within that district. For New Delhi, this data was collected for the period 1971 to 1993. Climatic potential yield was simulated for all these years. For other locations, the actual weather data of recent years was not available, therefore, long-term means of weather were used to estimate climatic potential yields. Actual grain yield data was available for only 84 locations used in the present analysis. Because actual yields are increasing with time, the maximum of the two recent (1988-89 and 1989-90) years yields was assumed to be the current actual yield of that location. The difference between climatic potential yield and actual yield was considered as the yield gap.

Effect of irrigation and nitrogen application In order to study the effects of irrigation and nitrogen, simulations were done for New Delhi environment alone, with 17 years of historical daily weather data. It was assumed that a medium duration cultivar was sown on 15

November on a 1.5 m deep soil with profile moisture at 75% of field capacity and with available nitrogen content of 0.8 kg ha^{-1} cm^{-1} of soil layer. Six irrigation treatments were simulated - no irrigation, one irrigation at 21 days after sowing (DAS), two irrigations (30 + 74 DAS), three irrigations (28+54+88 DAS), four irrigations (21+45+70+95 DAS) and five irrigations (21+45+68+86+110 DAS). Sixty mm water was applied at each irrigation. Fertilizer (120 kg N ha^{-1}) was added at the time of sowing. Effect of nitrogen was simulated for each of the six irrigation treatments. N application was varied from 0 to 250 kg ha^{-1}. When two or more irrigations were applied, 50% of the fertilizer was added at sowing and the rest was added to the surface soil layer in equal applications on 21 and 66 DAS. Fertilizer application was followed by irrigation. In rainfed treatments, the entire fertilizer was applied at sowing time whereas in one irrigation treatment, 67% was applied at sowing and rest a day before irrigation.

Results and Discussion

Climatically determined potential grain yields

Effect of latitude

Simulated potential grain yield varied between 2.56 to 8.25 t ha^{-1} depending upon location. Figure 4.1 illustrates isoquant lines of potential grain yield at different places in India. The yield potential was between 7 and 8 t ha^{-1} in north-western regions lying above 28°N. Between 24 and 28°N, potential yield varied from 6 to 7 t ha^{-1}. For the same latitudes, potential yield decreased with longitude. Potential yield varied between 4 t ha^{-1} and 6.5 t ha^{-1} between 20 and 24°N. In this region, inland positions generally had higher yield than the coastal areas. For latitudes below 20°N, potential yield was between 3.5 and 5 t ha^{-1} and generally increased with longitude.

These trends in yield appeared to be related to changes in mean temperature with latitude/ location. To test this hypothesis and to determine the magnitude of the effect, simulated yields were related to mean January temperatures. January was selected because tropical wheat climates have been classified based on mean January temperatures (Fischer and Byerlee, 1991) and this is the month with the lowest temperature of the year. The results indicated a strong linear decline in grain yield as the January temperature increased. For every degree increase in mean temperature (T), grain yields (GY) decreased by 428 kg ha^{-1} (GY t ha^{-1} = 13.3 – 0.428T; R^2 = 0.95, standard error of the estimate =0.32).

These results are based on mean climatic normals and for locations below 600 m asl. In practice, one may find a few locations where yield potential is different than suggested by this analysis. Such examples may be true because the emphasis in the present study was to establish trends of climatically potential yields across locations. The yields are also expected to increase with elevation and to vary due to climatic variability.

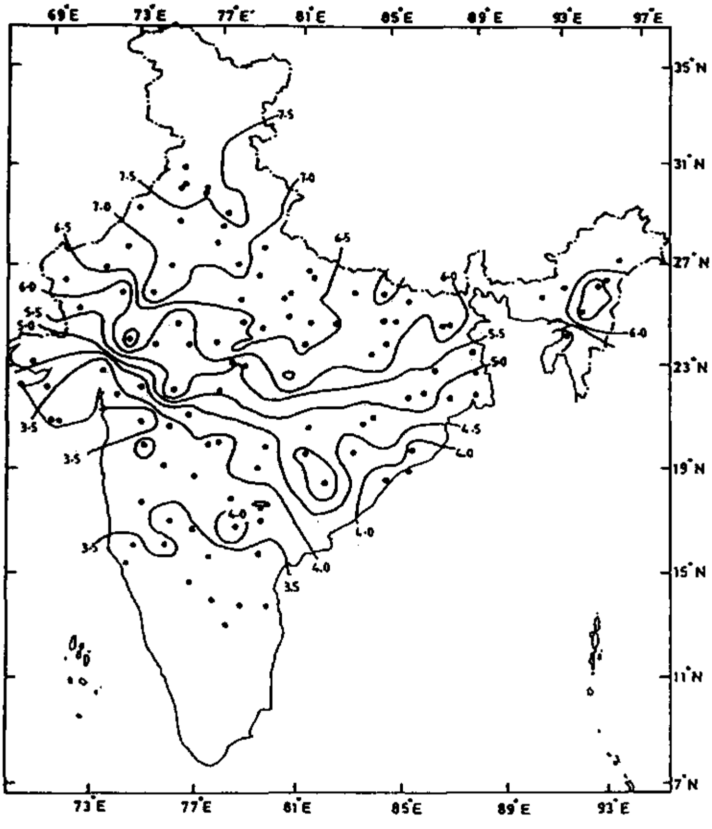


Figure 4.1. Lines of equal potential grain yield (t ha^{-1}) of wheat in different parts of India. All locations used in this analysis are below 600 m asl. Results are presented as isoquant lines of potential grain yield.

Effect of climatic variation

At all locations, climatic variation caused fluctuations in yield of more than 2 t ha^{-1} (Figures 4.2A and B). Frequency distribution analysis indicated that in 50% of the years, grain yield exceeded 6.8, 6.1, 5.9, 4.8, 3.0 t ha^{-1} for New Delhi, Pusa, Kota, Indore and Solapur, respectively. For these locations, the difference in grain yields between 75 and 25% probability levels was 1.0, 1.1, 0.5, 1.0 and 0.7 t ha^{-1}, respectively. Indices of yield variance (YVI) for these locations were 15.0, 18.3, 9.25, 20.2, 27.3%, respectively, indicating relatively high stability of wheat yields in north-western India (New Delhi, Kota) compared to other regions. Because weather in post-rainy wheat growing seasons is generally clear (the rainfall during wheat season is generally small), the major reason of yield variation in a location in different years was temperature. Figure 4.2A illustrates for New Delhi, the mean temperature for the months of December (vegetative development) and March (grain-filling period). Mean temperature varied between 13.2 and 17.9 °C in December and between 17.72

and 21.88 °C in March. Although there was no straight relationship, it is apparent that yield varied with temperature, in particular with the temperature in March; the higher the temperature the lower was the yield.

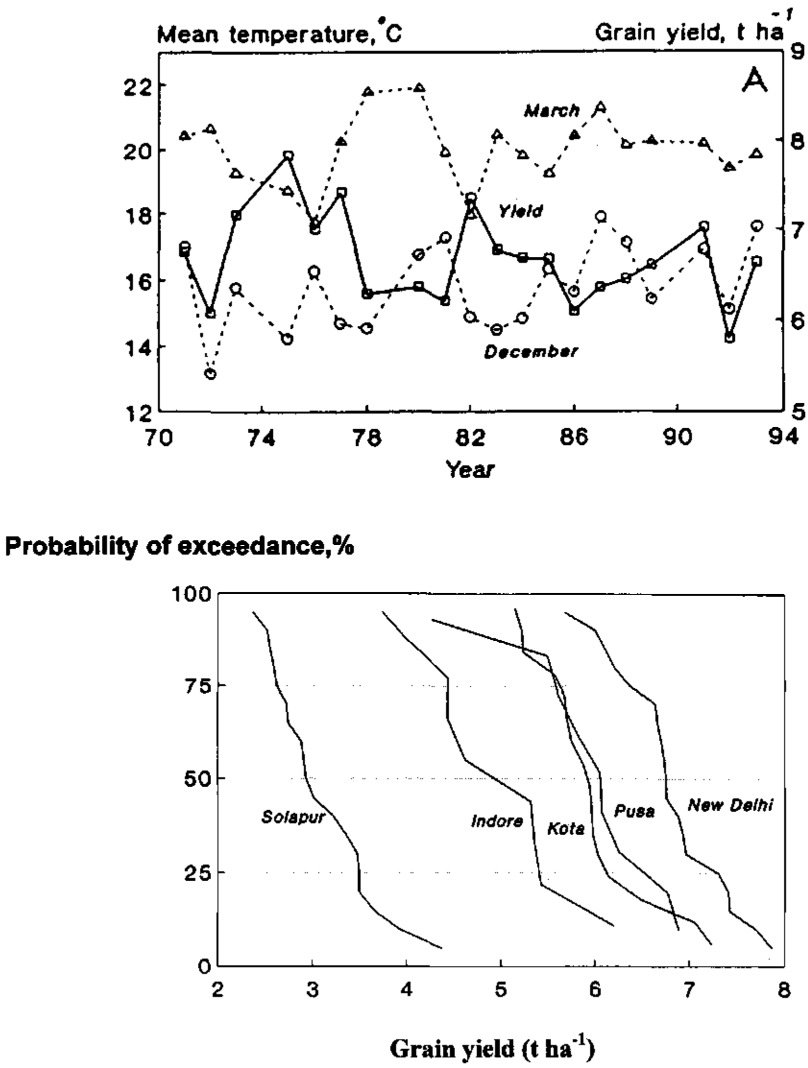


Figure 4.2. Effect of climatic variability on potential grain yields. Figure 4.2A illustrates the variation in mean temperature for the months of December (vegetative growth) and March (grain-filling), and potential grain yields during last 20 years at New Delhi. Cumulative probability distributions of potential grain yield for few key locations are shown in Figure 4.2B.

Effect of date of sowing

The effect of sowing date was simulated for all 138 locations. To facilitate presentation of results, the yield decrease per day delay in wheat sowing after 15 November is plotted against climatic potential grain yield of each location (Figure 4.3). It is apparent that as potential yield increased, the reduction in yield per day delay in sowing also increased. In general, the yield decrease was between 0.25% and 0.75% of potential yield when the latter was less than 4 t ha^{-1}, between 0.5 and 1.00% for yield potential between 4 and 6 t ha^{-1} and between 0.75 and 1.00% for yield potential greater than 6 t ha^{-1}. It was interesting that irrespective of potential yield, few locations showed a small yield reduction (less than 0.25%) with delayed sowing (Figure 4.3). Close examination of data revealed that these locations were from north-eastern parts of the country or from coastal regions where temperature and radiation varied less with time. However, in practice, there is very little wheat grown in these regions because of high incidence of pests and diseases and comparative advantage of growing other crops.

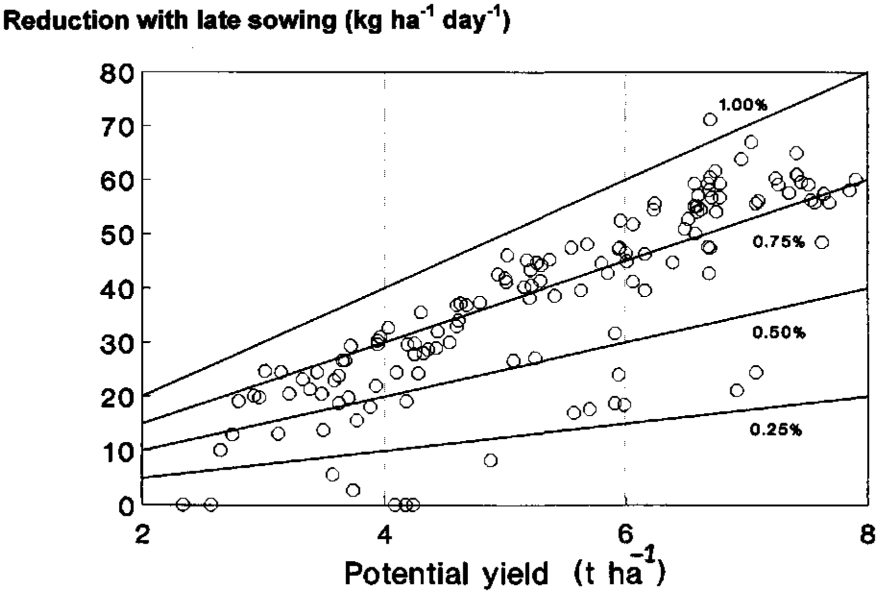


Figure 4.3. Reduction in grain yield with late sowing at different locations as a function of potential grain yield. Each point refers to a location. Also shown are lines indicating reduction of 1.0, 0.75, 0.50 and 0.25% in potential yield.

Interactions between sowing date and yearly climatic variation on wheat productivity were examined in detail for New Delhi. Maximum grain yield was obtained for sowings on 1 and 15 November. Grain yield varied between 5.2 t ha^{-1} and 8.5 t ha^{-1} for these sowing dates depending upon the year. At the 50% probability level, yield potential on both dates was 6.7 t ha^{-1} but in 75% years yield potential of 1 November exceeded that of 15 November although only by a relatively small amount (Figure 4.4). The index of yield variance was 16.9 and 9.8% for 1 and 15 November, respectively. Sowings done in December and January had much lower yields at all levels of probabilities. The median yields were 5.44, 4.62 and 3.73 t ha^{-1} for 1 December, 15 December and 1 January sowings, respectively. For these sowings stability of yield was also low as indicated by relatively higher values (20.9 to 28.3%) of YVI. If an adapted cultivar (early maturing) is grown in late sowings such as 1 January, yields were higher (4.48 t ha^{-1} at 50% probability level) compared to yield of a medium maturity cultivar (3.73 t ha^{-1} at 50% probability level) in all years. However, the yield variance was only slightly reduced as indicated by YVI (19.8 *vs* 20.9%). It can be concluded from the above results that in the New Delhi environment, grain yield was high and variance in yield was low for sowing done on 15 November. This can thus be considered as the optimal time of sowing. Late sowings had smaller yields as well as increased vulnerability to weather. On an average there was a decrease of 50 kg ha^{-1} day^{-1} delay in sowing.

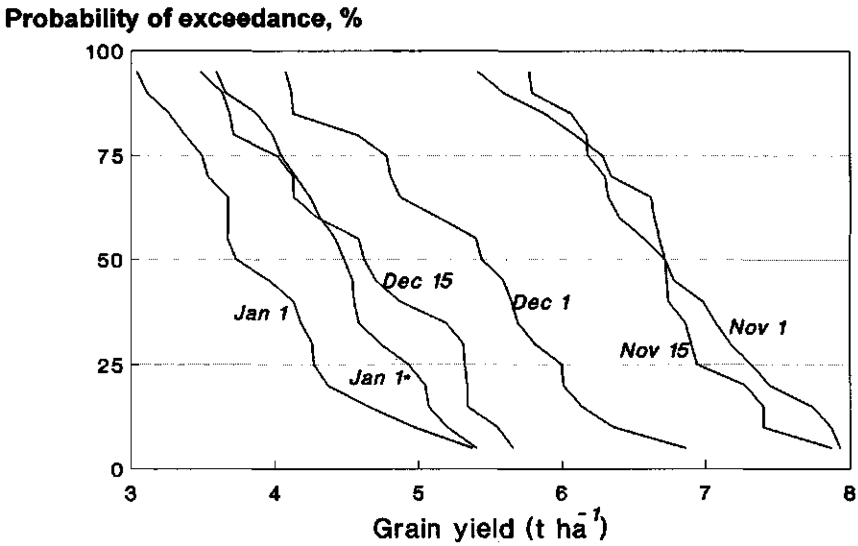
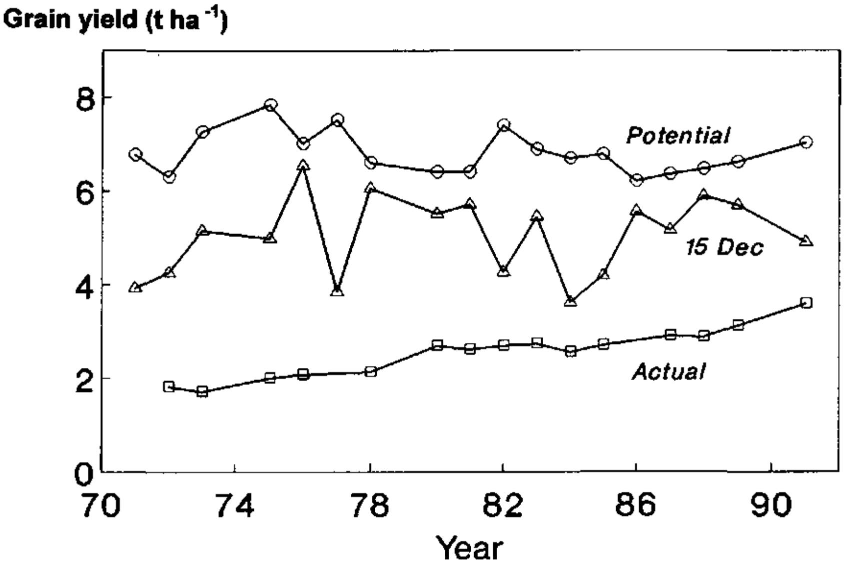


Figure 4.4. Cumulative probability distributions of potential grain yield as effected by date of sowing at New Delhi. The simulations were made for a medium maturity cultivar on all dates. For January 1 sowing, additional simulations were made for an early maturity (Jan 1*) cultivar as well. The distributions are based on simulations of 18 crop seasons.

Yield gap

Climatic potential grain yield at New Delhi varied between 5.6 t ha^{-1} and 8.0 t ha^{-1} depending upon the year. Actual grain yields were low (< 2 t ha^{-1}) in 1970s, rose to 3 t ha^{-1} in 1980s and are now above 3 t ha^{-1} (Figure 4.5A). This illustrates that although actual yields have almost doubled in the last 25 years, still there is at least a 2 t ha^{-1} yield gap between climatic potential yield and actual yield. A large part of this gap is due to delayed sowing, which is common in the region (WPD, 1989). It is evident from Figure 4.5A that depending upon the year, 0.5 to 2.5 t ha^{-1} of yield gap could be simply the result of late sowing.



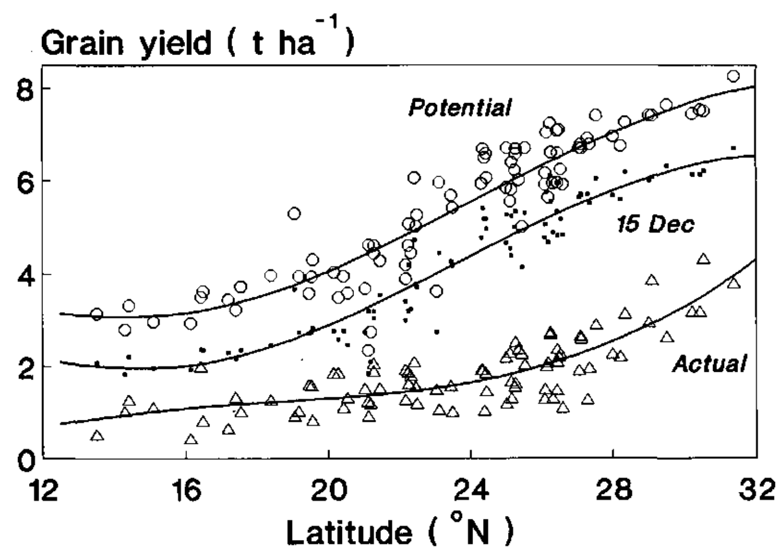


Figure 4.5. Gap between climatic potential grain yields and actual yields a) for various years at New Delhi and b) at different locations in India (shown as a function of latitude). Simulated potential yields for a 15 December sowing is also shown to illustrate the contribution of late sowing in yield gap. Actual weather data was used for estimating potential yields for New Delhi and long-term climatic means for other locations.

In order to determine yield gaps at different locations, climatically determined potential grain yields and actual yields at these locations were plotted against latitude (Figure 4.5B). Because in most states considerable proportions of wheat are sown in December and January (WPD, 1989), climatically potential grain yields for 15 December sowing are also plotted. It is apparent that yield potential increased with latitude although the rate of increase varied. For latitudes below 18°N yields were not affected by latitude; climatic yield potential was 3.3 t ha^{-1}, yield potential for December 15 sowing was 2.1 t ha^{-1} and the actual grain yield was 1 t ha^{-1} indicating a yield gap of 2 t ha^{-1} or more. Almost 50% of this gap could be ascribed to sowing date effects. From 18°N to 25°N, potential yields at optimal sowing date as well as for 15 December sowing showed a steep linear increase with latitude; the rate of increase for both sowings was approximately 0.4 t ha^{-1} $°N^{-1}$ latitude. Actual yields however showed a small response to latitude - ranging from 1 t ha^{-1} at 18°N to 1.5 t ha^{-1} at 25oN. This indicates that there was a large yield gap which increased with latitude and only a small portion could be explained by sowing date effects. Most of this area is rainfed or receives limited irrigation which apparently might be the major yield reducing factor. At higher latitudes, which is the main wheat belt of India, yield potential was always higher than 6 t ha^{-1}. Actual yields here showed a distinct linear increasing trend; yields increased from 1.5 t ha^{-1} to 4 t ha^{-1} as the latitude increased from 26°N to 31°N. Nevertheless, at all latitudes there was a considerable yield gap. In general, the results showed a yield gap of at least 2 t ha^{-1} at all places. A significant portion of this yield gap was due to delayed sowing. As much as 1.5 t ha^{-1} gap could be explained by 1 month delay in sowing. There is a need to examine soil factors and other management practices to analyse the causes of larger yield gaps. The use of long-term mean weather data to estimate climatically potential grain yields could have resulted in some error in estimation of yield gap in the above analysis. However, in view of large yield gaps in almost all locations, the error is expected to be small.

Effect of irrigation

The simulated rainfed yields at New Delhi varied from nil to 3.6 t ha^{-1} depending upon the year. In 20% of the years crops died before maturity due to severe water stress. Cumulative probability distribution of rainfed yields showed that there is a 25, 50 and 75% probability of yield exceeding 2.6, 1.7 and 0.9 t ha^{-1}, respectively (Figure 4.6). Although rainfall during wheat growing season is low (75 mm on an average), it is sufficient to have a significant impact on grain yield because it is received during critical periods of early vegetative growth. Application of one irrigation at 21 DAS significantly increased grain yield in all years. At 25, 50 and 75% probability levels grain yield was 3.8, 2.8 and 1.6 t ha^{-1}, respectively indicating a minimum of 1t ha^{-1} increase in yield in 50% years and almost 0.5 t ha^{-1} in others. Additional irrigation at 74 DAS (two irrigation treatment) further increased yield in all years (Figure 4.6). The yields at 25, 50 and 75% probability levels were 4.9, 3.9 and 3.2 t ha^{-1} respectively, suggesting a yield increase of one t ha^{-1} or more in most years.

When three irrigations were applied, there was a significant increase in yield in all years (Figure 4.6). In this treatment yield varied from 2.8 t ha^{-1} to 5.7 t ha^{-1}. Relative to two irrigation treatments, yields at 25, 50 and 75% probabilities were 5.5, 4.8 and 4.0 t ha^{-1}

respectively. The relatively small differences in these yields indicate considerably reduced climatic vulnerability of wheat crops in this treatment.

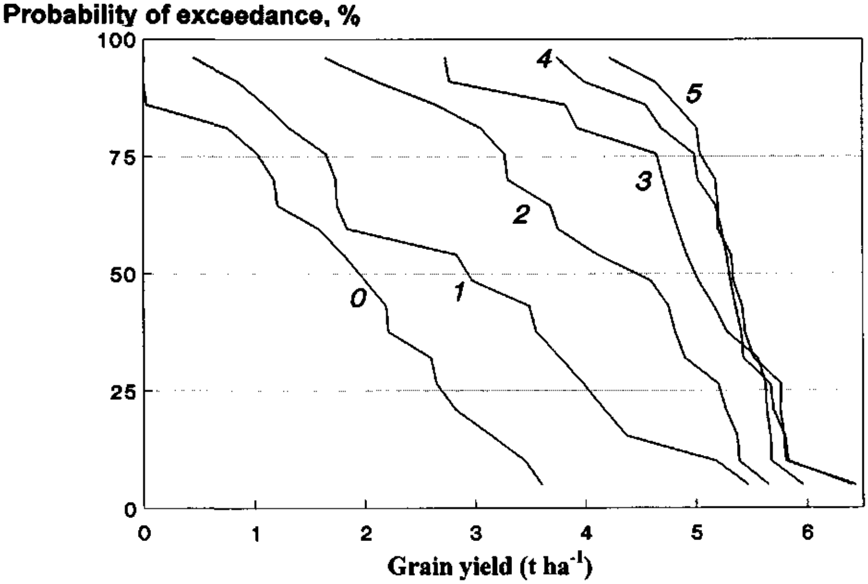


Figure 4.6. Effect of application of different numbers of irrigations on cumulative probability distributions of grain yield at New Delhi. Irrigation treatments are shown in text.

Application of additional irrigation at the grain-filling stage (four-irrigation treatment) did not result in any yield increase in 35% years; in others there was an increase varying from 0.1 t ha^{-1} to 0.9 t ha^{-1} (Figure 4.6). The magnitude of variation in yield in different years was further reduced as indicated by relatively small difference at different levels of probabilities. The conventional recommendation of five irrigation applications (Singh, 1986) had no beneficial effect on yield compared to four irrigation treatments in 70% years while in the remaining 30% the response was very small (Figure 4.6).

It can be concluded that considering the climatic variability of New Delhi, application of three irrigations during crop season produces yield which in 75% years is at least 90% of yield achieved by four to five irrigations. Thus, considerable increase in water use efficiency and hence saving in water could be made without any significant reduction in grain yield by providing only three irrigations. However, the demand of water might also vary if the soil moisture at the time of sowing is less than 75% of field capacity or the soils are shallower than 150 cm, as is assumed in this case study.

Optimal time of limited irrigation

Because application of one and two irrigations had very large effect on yield (Figure 4.6), simulations were done for determining their optimal time of application. Two irrigations, 60 mm each, were applied at different times after sowing as per Figure 4.7. Simulations were made for four treatments- first irrigation was given at 21 DAS (approximately crown root initiation stage) in two treatments and at 46 DAS (early vegetative stage) in others. The time of application of second irrigation was either 86 DAS (pre-flowering to flowering stage) or 106 DAS (grain-filling stage). The results showed that in 75% years, yields were higher if the second irrigation was given at 86 DAS. In remaining years, yields were relatively larger when the first irrigation was given at 21 DAS. If the second irrigation was delayed further, there was a small reduction in yield in 40% years, in rest the yield was reduced by 10% to 30%. This indicates that the wheat crop has enough capability to compensate for growth reduction if stress is relieved few weeks before flowering. Once grain development and then grain-filling starts, there is reduction in grain yield depending upon the level of stress. These results are also supported by the studies of Nix and Fitzpatrick (1969) where a close relation of yield with moisture at the time at anthesis was observed.

Interaction of Irrigation with Nitrogen

Median yields (at 50% probability level) of different treatments are presented in Figure 4.8A and yield variance index (YVI) in Figure 4.8B. Rainfed yields were 1.94 t ha^{-1} when no fertilizer was applied. Yield increased marginally to 2 t ha^{-1} when 25 kg N ha^{-1} was applied. Additional fertilizer had no effect; in fact, yields were reduced with fertilizer application in some years (data not shown). Fertilizer increased pre-anthesis growth which exhausted water early thus exposing crops to the risk of post-anthesis water stress. There was a very large effect of climatic variation on rainfed grain yield as is indicated by very high (90%) YVI. There was no significant effect of N application on YVI.

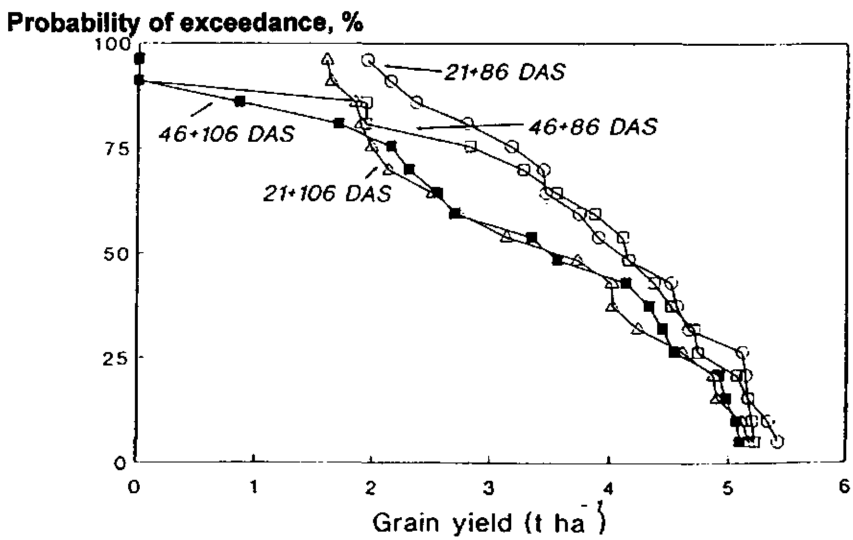


Figure 4.7. Effect of time of application of two irrigations on probability distributions of wheat grain yields at New Delhi.

Grain yield increased and its variance was reduced with irrigation. One irrigation increased median yield to 2.71 t ha^{-1} without N application. A modest application of 25 kg N ha^{-1} resulted in a significant (20%) increase in grain yield, but greater N application resulted in only 8 to 16% increase (Figure 4.8A). The YVI was low (24.7%) with no N but increased rapidly and almost linearly to 80% with 100 kg N ha^{-1} indicating significant interaction of N with climatic variability. The index was slightly reduced at still higher levels of N application (Figure 4.8B). It is clear that yield variance increased proportionally with the amount of fertilizer. Application of 25 kg N ha^{-1} resulted in maximum increase in median yields (Figure 4.8A). Greater fertilizer application resulted in higher yields in some years whereas in others yields were reduced, the magnitude of decrease increased with the quantity of fertilizer applied (data not shown). Application of 50 kg or more N ha^{-1} resulted in yields that were lower than those of unfertilized plots in several years. It can be concluded that when water availability is low, addition of fertilizer should be kept lower than 50 kg ha^{-1} in order to maximize returns in grain yield and to keep yield variance at low levels. Greater applications of N leads to proportionately higher consumption of water during pre-anthesis stage and thus exposing the crop to risks of accelerated water stress during grain-filling stages.

When two irrigations were applied, yield up to 25 kg N ha^{-1} application was similar to that of one irrigation but further N application up to 100 kg ha^{-1} increased yields rapidly to 4.4 t ha^{-1} There was only a very small response to higher doses of N fertilizer. The application of two irrigations relative to single irrigation had no significant effect on YVI at zero N level but YVI was substantially reduced at all other levels of N (Figure 4.8B). The index was 22 to 26% till 50 kg N ha^{-1} application and 38 to 43% at higher N levels.

The results also show that to take full advantage of three irrigations, N application should be at least 50 kg ha^{-1} (Figure 4.8A). At this N level as well as at 100 and 150 kg ha^{-1}, yield increase over two irrigation treatments was 0.5 t ha^{-1}. This difference increased to 0.7 t ha^{-1} at still higher levels of N application. Thus, in three irrigation treatment, increase in grain yield was 28 kg ha^{-1} per kg N up to an application of 50 kg N ha^{-1}. Subsequent increase in N application up to 150 kg ha^{-1} resulted in only 7 kg ha^{-1} increase in yield per kg N. The vulnerability to climate was substantially reduced by three irrigations (YVI=17%). Application of N had only a very small effect on this. If number of irrigations was further increased from three to four or five, relatively yield increased only when N applied was 150 kg ha^{-1} or more. The increase was 0.31, 0.49 and 0.57 t ha^{-1} at 150, 200 and 250 kg N ha^{-1}. Yield variance was further reduced by irrigation but N level had no significant effect on this reduction.

It can also be noted from Figure 4.8A that same yield is achieved by different combinations of irrigation and N fertilizer. For example, a yield of 4 t ha^{-1} could be obtained by 50 kg N ha^{-1} and 180 mm irrigation as well as by 100 kg N ha^{-1} and 120 mm irrigation. Similar substitution between these two inputs has been shown by field experiments of Gajri et al. (1993). In either case, the roots were able to go deeper and compensate the crop with the substituted input.

The above described interaction of N, irrigation and climatic variability particularly at low input usage has several important implications. Firstly, at low levels of water availability it is difficult to decide optimal levels of N fertilizer for maximizing yield returns in view of uncertainty of response until late in the season. This may also explain farmers' reluctance to apply inputs due to uncertainty of weather and hence returns to inputs use. This uncertainty may be still greater for regions where climatic variability is greater than in New Delhi. However, because crops responded to N in many years, strategies are needed for deciding tactically about the quantity and timing of fertilizer applications. This may help reduce the level of inputs use without losing productivity. Simulation models are now being used for such purposes as well (Angus et al., 1993). Secondly, conclusions drawn from experimental research on optimal fertilizer levels from few years of experimentation may not be valid unless supported by crop growth simulation for a large number of years to account for the climatic variability.

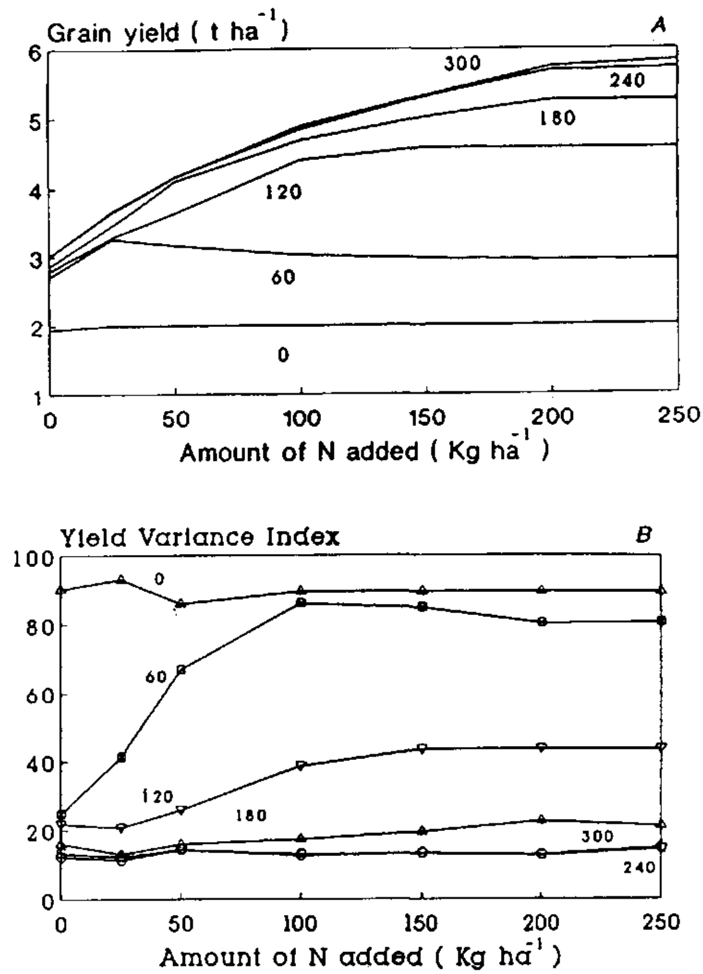


Figure 4.8. Effect of amount of N fertilizer added at different levels of irrigation application on (A) median grain yields (at 50% probability level) (B) yield variance index of wheat at New Delhi.

General Conclusions

Analyses done using crop growth model, WTGROWS, reveal that in most regions of India where wheat is currently produced, climatic factors allow considerable yield potential. This potential increases with latitude and is related to temperatures during crop season. Although wheat in India is grown in the post-rainy season with very few cloudy days, potential yields show considerable variance due to yearly trends in climatic variability. Delay in sowing results in a sharp decrease in grain yield. In general, the higher the yield potential the higher is the loss per day delay in sowing. Comparison of actual yields and simulated climatically potential grain yields show a yield gap of 2 t ha^{-1} to 4 t ha^{-1} depending upon the location. A large fraction of this could be attributed to delayed sowing time.

Crop simulation with different amounts of nitrogen and irrigation showed significant effect of interaction between water and N availability on grain yield particularly at low levels of inputs usage. In order to achieve higher yields there is a need to maintain crops free from water stress a few weeks before flowering and grain-filling. Application of three irrigations during crop season produced at least 90% of yield achieved by still more number of irrigations in 75% years. The amount of N fertilizer applied to crops should have a close link to the amount of irrigation and should consider climatic variation as well. Yield variance of stressed wheat crops is greatly moderated by irrigation but at low levels of application, N fertilizer may modify the response.

The significant interaction effects of irrigation and nitrogen on wheat productivity and substitution of each other to a certain extent as indicated by crop simulation is also suggested by field experiments. This demonstrates the capability of the simulation approach in replicating qualitative as well as quantitative results of field experiments. It can be concluded that crop simulation can serve as a useful tool to optimize use efficiency of water and nitrogen in environments varying in climatic factors as well as level of input use.

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5. A systems approach to analyse production options for wheat in India

Abstract

In this chapter, we illustrate the use of systems tools such as simulation models, GIS, databases and optimization techniques for determining potentials, constraints and opportunities for further increase in productivity of wheat in different districts of India. The whole country has been considered as a mega eco-region and its districts as sub-ecoregions because most planning is done following these administrative boundaries.

In a large number of districts spread over the states of Punjab, Uttar Pradesh (U.P.), Bihar, Assam, Rajasthan, and Madhya Pradesh (M.P.), potential yields were 7 t ha^{-1} or more. Most districts in U.P. have a yield potential between 6 to 6.5 t ha^{-1}. The potential yield was between 5 and 6 t ha^{-1} in middle latitudes and states of West Bengal and M.P.. Economically optimal levels of N fertilizer application in irrigated environments were estimated for all locations based on current price ratios of N fertilizer and grain, native soil fertility, simulated crop response to N fertilizer and other costs related to transport, harvesting and market forces. A comparison of optimal and actual N applications showed that in Ludhiana district of Punjab, N application is more than the simulated optimal whereas in other districts it is at par or lower. The estimated yields corresponding to the profit maximizing amount of N application (henceforth referred as optimal economic yields) were generally 200 to 500 kg ha^{-1} lower than the potential yield irrespective of the location. The small difference between potential and optimal economic yield is due to distorted but favourable price ratios at present. In rainfed environments, optimal economic yields would be still lower. At most locations, there was a large yield gap. At higher latitudes, the main wheat belt of India, yield gap of 2 t ha^{-1} was common even in well-irrigated regions. Almost 35-50% of the gap could be ascribed to delayed sowing, common in a number of districts. Factors such as limited and timely availability of irrigation and fertilizers, cropping pattern and access to credit and other services are some of the other principal causes of yield gaps.

Introduction

Increasing population, urbanization and income growth are resulting in a rapidly increasing demand for food in India as well as many other developing countries (Pinstrup-Anderson, 1995). It is estimated that the total food grain requirement of India will increase from the present level of approximately 200 Mt to 246 Mt by 2010 and 294 Mt by 2020 (Kumar, 1998). There is, therefore, a need to know the agricultural productivity potential in different agro-climatic zones of the country to determine whether India can produce this much, where, and how.

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In order to identify the constraints limiting productivity at present and opportunities for sustainable increase in future, it is important to analyse the various factors constituting a production environment. The latter is made up of natural resources such as soil fertility, germplasm, level of inputs usage, opportunities allowed by climate, interactions with climatic variability, services providing assistance to farmers such as credit facilities, and market forces. Interactions among these factors often make decision making a difficult process in many production systems of today. Such situations need an eco-regional approach to apply inter-disciplinary knowledge to help focus on region specific problems and their optimal solutions (Rabbinge, 1995).

In view of the considerable diversity in India's physical, biological and socio-economic production environment, it is also necessary to demarcate homologous agro-ecological zones. Such zones are appropriate as a framework to develop data inventories of environmental resources which may show spatial and temporal variations. They help in linking physical, biological and socio-economic attributes to the performance of a crop. Extrapolation of research results from selected sites to throughout the homogenous zone can be made more effectively through such tools.

Several attempts have been made to classify India's diverse climates for making effective land use plans. The Planning Commission of Government of India carved 15 agro-climatic zones based on physiography and climate (Government of India, 1987). Subsequently, these were sub-divided into 127 agro-ecological zones by the National Agricultural Research Program (NARP) based on physiography, rainfall, soils, cropping pattern and administrative boundaries (Ghosh, 1990). The National Bureau of Soil Survey and Land Use Planning superimposed soil texture map, physiography, climate (aridity-humidity) and computed length of growing period to demarcate 21 zones in whole of India (Sehgal et al., 1990). These agro-ecological zoning efforts have been principally based on considerations of rainfall and to some extent on soil texture. Major quantitative output of these analyses is the difference in growing period between regions. From a purely ecological view point, this may be adequate but when the primary interest is in the knowledge of agricultural potential of a region and its development, one needs to know much more, for example, the yield potential of crops, optimal crop duration and major constraints limiting yield. Aggarwal (1993) argued that the growing period based agro-ecological zoning is appropriate only when agriculture is based on monoculture cropping and rainfall is the principal variable determining crop yield such as in large tracts of semi-arid tropics. With the increased availability of irrigation resources (> 70% of Indian wheat is now irrigated) and increased cropping intensity during last few decades, there is now a need to reconsider the main variables affecting crop growth and yield and hence agro-ecological zoning.

The major biotic and abiotic factors affecting crop growth and development in any production system are radiation, temperature (yield-determining), water, nutrition (yield-limiting), and pests, weeds and diseases (yield-reducing) (Rabbinge, 1993). In addition, productivity is also determined by many other factors such as variety, its physiology and crop management which interact with weather and soils to influence yield level. Systems tools such as simulation models, GIS, databases and optimization technologies now offer exciting opportunities to understand dynamic interactions among various components of production systems.

In this chapter, we illustrate our approach for documenting and analysing current production environment of wheat, a major food crop, in different regions of India and to determine options for further increase in productivity. The whole country has been considered as one mega eco-region. Since most planning is done following administrative boundaries, districts are chosen as the primary land evaluation units. This is the smallest unit for which dependable primary data such as on cropped area and productivity is readily available. This is largely an explanatory type of study aimed at understanding limitations and opportunities due to biophysical factors. More specifically, the objectives are:

1. To determine the potential and optimal economic yields of wheat in different land evaluation units and to demarcate regions with similar yields.
2. To quantify the magnitude of the yield gap and its principal causes in different regions.

Current Yields

Wheat is grown in diverse agro-climatic conditions from 11°N to 35°N , from 72°E to 92°E and from almost sea level to very high elevations. The major wheat producing areas are between 20°N and 32°N comprising the states of Punjab, Haryana, Uttar Pradesh (U.P.), Madhya Pradesh (M.P.), Rajasthan, Bihar, West Bengal and Maharashtra. Table 5.1 lists wheat area, percent wheat area under irrigation, fertilizer consumption, and average yield for some key wheat producing states of India. In Punjab and Haryana, almost the entire area is irrigated and average fertilizer application is relatively high. This results in higher yields compared to other states. There is nevertheless considerable variation at the district level. In Punjab, yield varies 2 from t ha^{-1} to 4 t ha^{-1} depending upon the region. U.P. state alone accounts for 1/3 of the total wheat area of the country. Most of this area is irrigated, average fertilizer use is modest and crop yields are relatively low (2 t ha^{-1}). In western parts of the state, yields are more than in the eastern parts. In Rajasthan, although 90% wheat is irrigated, fertilizer consumption is very low and yet the productivity is comparable to U.P. state. M.P. has a large proportion of rainfed wheat, fertilizer consumption is low and so are the yields.

There has been a rapid diffusion of modern varieties all over India particularly in irrigated areas. Locally adapted varieties are continuously developed and released by wheat breeders to maintain disease resistance.

Area growth at present is almost negligible in all states except Rajasthan (Table 5.1). Growth rate in yield is low (2.2 - 2.3%) in Punjab and U.P. and modest (2.5 - 3.5%) in other states (Table 5.1).

A significant portion of the yield variation in different parts of India could be related to climatic differences. The temperatures during the crop season vary a lot depending upon the latitude. From south to north, mean January temperature varies by 15 °C. Temperatures in Punjab and Haryana states are relatively low compared to U.P., Bihar, M.P. and Rajasthan. Photothermal quotient (radiation/temperature), related to growth and yield of wheat crops (Fischer, 1985), is almost similar in most states of northern India but is relatively low in eastern and central regions (Aggarwal, 1994). Seasonal rainfall is about 100 mm in many parts of Punjab and northern U.P. and is less than 50 mm in most parts of central and eastern India. Because rainfall is limited, crops depend upon stored soil moisture and irrigation for meeting their water requirements.

Table 5.1. Basic statistics on wheat for major wheat producing states of India.

State	Total area[1]	Productivity[1]	Irrigated area[2]	Fertilizer use[1]	Growth rate[3]		
	Mha	t ha^{-1}	% of total	kg ha^{-1}	Area	Production	Yield
Uttar Pradesh	8.66	2.05	88	86	0.82	3.14	2.30
Punjab	3.25	3.59	95	156	0.71	2.93	2.20
Haryana	1.86	3.18	98	114	1.53	5.05	3.47
Bihar	1.97	1.64	81	55	0.40	2.95	2.54
Madhya Pradesh	3.20	1.21	39	30	−0.23	2.79	3.03
Rajasthan	1.65	2.06	90	21	2.32	5.72	3.32

[1] 1989-90 data [2] 1987-88 data [3] 1985-86 - 1990-91.

Potential Yields

In view of the large differences in actual yield in different regions, it is important to know the opportunities allowed by the climate of that region. Potential yield is the integrated expression of the influence of radiation and temperature on crop growth and development of a particular crop/variety. The production system is characterized by adequate water and nutrient supply and absence of all yield reducing factors such as pests and diseases. Potential yield can be interpreted as the upper limit that can be achieved by the current varieties in a no-constraint environment.

The methodology used for estimation of potential wheat yields was described in Chapter 4. WTGROWS and long-term weather data of several locations spread over the entire country were used to estimate the yield potential of wheat. Potential yield for each district was interpolated from individual location yield. Digitized maps comprising district boundaries, soils, weather stations and agro-ecological regions were stored in GIS packages ARC-INFO and IDRISI.

In a large number of districts spread over the states of Punjab, U.P., Bihar, Assam, Rajasthan, and M.P., potential yields were 7.0 t ha^{-1} or more (Figure 5.1). Most districts in U.P. have a yield potential between 6.0 to 6.5 t ha^{-1}. The yield was between 5.0 and 6.0 t ha^{-1} in middle latitudes and states of West Bengal and M.P. In most districts of Gujrat, Maharashtra and Orissa, potential yield was only 4.0 to 5.0 t ha^{-1}. Agro-climate of southern states of Andhra Pradesh, Karnataka, southern and coastal Maharashtra did not allow yield potential to exceed 4.0 t ha^{-1}. These geographical trends in yield potential were apparently related to changes in mean temperature changes with latitude/location (Chapter 4).

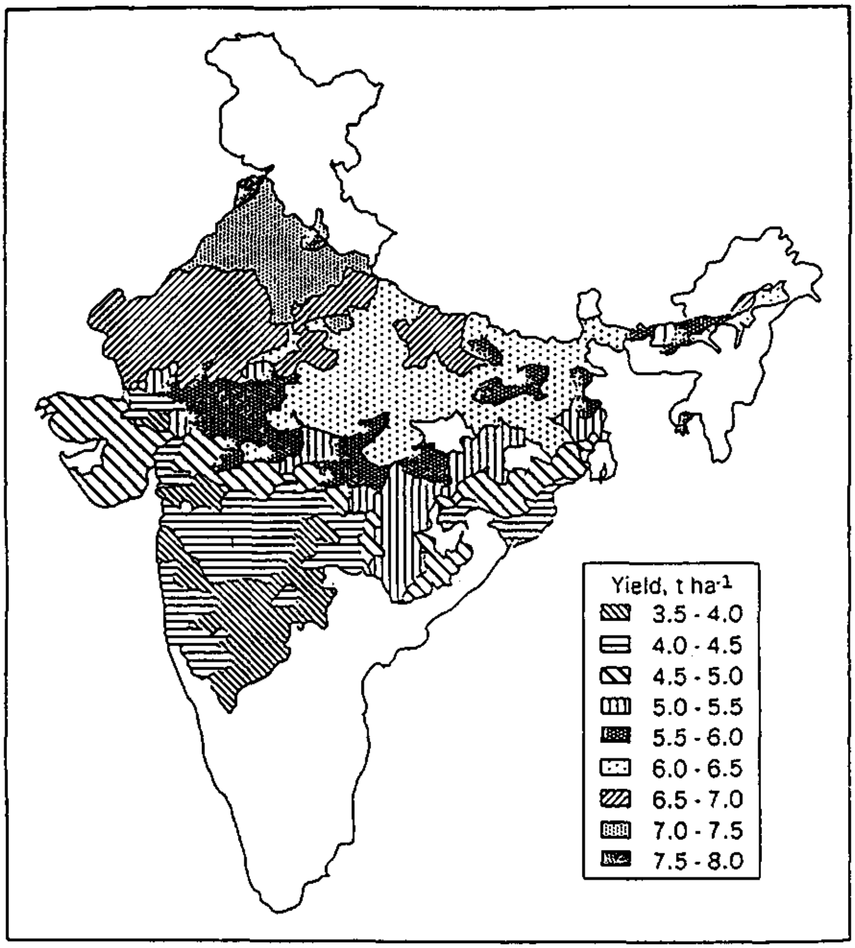

Figure 5.1. Potential yields (t ha^{-1}) of wheat in India. Only those districts are labelled where wheat cultivation is significant.

Optimal N Application and Economic Yields

Potential yields as estimated above may not be economically optimal. The later depends on cost of cultivation and net benefit:cost ratio. Normally, optimal levels are defined considering the whole production system and component crops, and opportunity costs outside agriculture but this analysis refers to cultivation of wheat alone. We made studies to determine economically optimal levels of N fertilizer application in irrigated environments based on current price ratios of N fertilizer and grain, native soil fertility, N response and other costs related to transport, harvesting and market forces (Aggarwal et al., unpublished). The basic level of soil fertility is low in most Indian soils (Ghosh et al., 1978). Initial soil N profile in the model was calibrated to these low levels. Of course, this level is dynamic and would be very much dependent upon cropping history, but for simplicity, uniform level at the time of wheat sowing was assumed for all locations. The geographical distribution of soils was obtained from the agro-ecological zones map of India (Sehgal et al., 1990). The dominant soil textures of wheat growing regions are loam sand, sandy loam, black and red loam. For each of these textures, a representative water retention profile was used (Kalra et al., 1995). Simulations indicated that irrigated fields with no fertilizer application can produce between 1.5 to 2.5 t ha^{-1} depending upon the region. Indeed, Goswami et al. (1979) based on approximately 2000 experiments conducted over several seasons in many locations showed that this fertility level is sufficient to produce 1.5 to 2.0 t ha^{-1} yield depending upon the place without any fertilizer application. The crop model was then used to simulate fertilizer response for all locations used for determining potential yields. It was assumed that fertilizer is applied in two splits: at sowing (2/3) and at crown root initiation (spike initiation) stage (1/3), and other nutrients and biotic factors are not a constraint. Marginal physical productivity was estimated from the quadratic crop N response curves. The current price ratio for N *vs.* grain was estimated to be 4.66 considering the costs of urea, transport costs of fertilizer, cost of fertilizer application, gate price of grain, cost of additional harvesting and opportunity costs of investment (Aggarwal et al., unpublished). Based on this price ratio, the optimal N application rate was calculated.

The simulated optimal N rate varied between 75 to 185 kg ha^{-1} depending upon the location. In most parts of U.P., optimal N rate was between 150-170 kg ha^{-1}. In most districts of Bihar, Rajasthan, Punjab, Haryana and some parts of U.P., it was between 130-150 kg ha^{-1}. These variations were a consequence of interactions among native soil fertility, soil physical properties, and weather factors. A comparison of optimal and actual N applications showed that in Ludhiana district of Punjab, N application is more than the simulated optimal whereas in other districts it is at par or lower. In other states, actual N application was lower than the simulated optimal (Table 5.2).

Optimal economic yields are defined as the level where profit of N use was maximum. These yields were estimated by inputting optimal N rate in the quadratic response curve of yield *vs.* N. Since prices are dynamic, the optimal N rate would not be the same every year. Nevertheless, this would not significantly alter estimates of grain yield in many irrigated areas where yield response to N fertilizer is near plateau. Many other factors such as phosphate fertilizers application, pesticide and labour use would also determine optimal economic level of grain yield. Optimal levels would be different if the whole production system and opportunity costs of a farm were considered. A more appropriate approach would perhaps be to do a total factor productivity analysis considering biophysical and socio-economic factors together. Recent trends nevertheless indicate that fertilizers constitute a major share of the operational costs, particularly in wheat production in Punjab, Haryana and U.P. (Anonymous, 1991a) and more than 70% of the total fertilizer applied to wheat is nitrogen.

The results showed that optimal economic yields were generally 200 to 500 kg ha^{-1} lower than the potential yield irrespective of the location. In a few high latitude locations, the difference was greater than 500 kg ha^{-1} perhaps due to interaction effects with irrigation. The small difference between potential and optimal economic yield is due to distorted but favourable price ratio at present. It can be noted that the price of urea has decreased significantly in the nineties compared to the seventies and eighties (Figure 5.2). Simultaneously there has been an increase in net price of wheat. Nevertheless, the price ratio of N and grain has come down allowing farmers to apply more N. This greater application of N at the margin, however, results in only small gains in productivity and reduces overall technical efficiency of N use. The optimal economic yield was between 6 and 6.5 t ha^{-1} in some parts of U.P. and most of Punjab. In most parts of U.P., Bihar and Rajasthan the optimal economic yields were between 6 and 6.5 t ha^{-1}. In the state of M.P. these yields varied between 5 and 6 t ha^{-1}. It must be remembered that these estimates are for well irrigated fields with no biotic and abiotic constraints. Such situations are not very common. In rainfed environments, such as those in large areas in M.P. and Bihar, optimal economic yields would be lower than those estimated by us. Also, optimal economic yields are dynamic because of temporal and spatial variations in prices, soil physical properties and biophysical factors.

Table 5.2. Actual and simulated optimal N application in few selected districts of Punjab and U.P. states (Aggarwal et al., unpublished). Actual application was estimated from rabi (wheat season) N off-take by the estimated share applied to wheat (0.9 for Punjab and 0.75 for U.P.).

	N application, kg ha^{-1}	
District	Actual	Optimal
Punjab		
Ludhiana	191	171
Amritsar	158	159
Patiala	110	169
UP		
Varanasi	116	175
Kanpur	119	179
Agra	143	162
Bareilly	150	170
Saharanpur	128	168

Yield Gap

Actual grain yields obtained by farmers on a regional basis are reported every year by the Government of India. The smallest reporting unit is a district. Data for all districts was collected for the years 1988-89 and 1989-90 (Anonymous, 1990, 1991). The maximum of the two years yields was assumed to be actual yield of that location. There are indications that at present actual yields are 10 - 15% more than these estimates but recent detailed data was not available. The difference between optimal economic yield and actual yield was considered as the yield gap.

In order to determine yield gaps at different locations, potential, optimal economic and actual yields at these locations were plotted against latitude (Figure 5.3). It is apparent that yields increased with latitudes although the rate of increase varied. For latitudes below 18°N optimal economic yield was 3.5 t ha^{-1} and the actual grain yield was 1.2 t ha^{-1} indicating a yield gap of 2.0 t ha^{-1} or more. From 18°N to 25°N, optimal economic and potential yields showed a steep linear increase with latitude. Actual yields however showed a small response to latitude - ranging from 1.0 t ha^{-1} at 18°N to 1.5 t ha^{-1} at 25°N. This indicates that there was a large yield gap which increased with latitude. Most of this area is in central India and is rainfed or receives limited irrigation which apparently might be the major yield reducing factor. At higher latitudes, which is the main wheat belt of India, potential yield was always greater than 6 t ha^{-1} and optimal economic yield was about 6.0 t ha^{-1}. Actual yields here showed a distinct linear increasing trend with latitude; yields increased from 1.5 t ha^{-1} to 4.0 t ha^{-1} as the latitude increased from 26°N to 31°N. Nevertheless, at all latitudes there was a considerable yield gap. In general, the results showed a yield gap of at least one t ha^{-1} at all places.

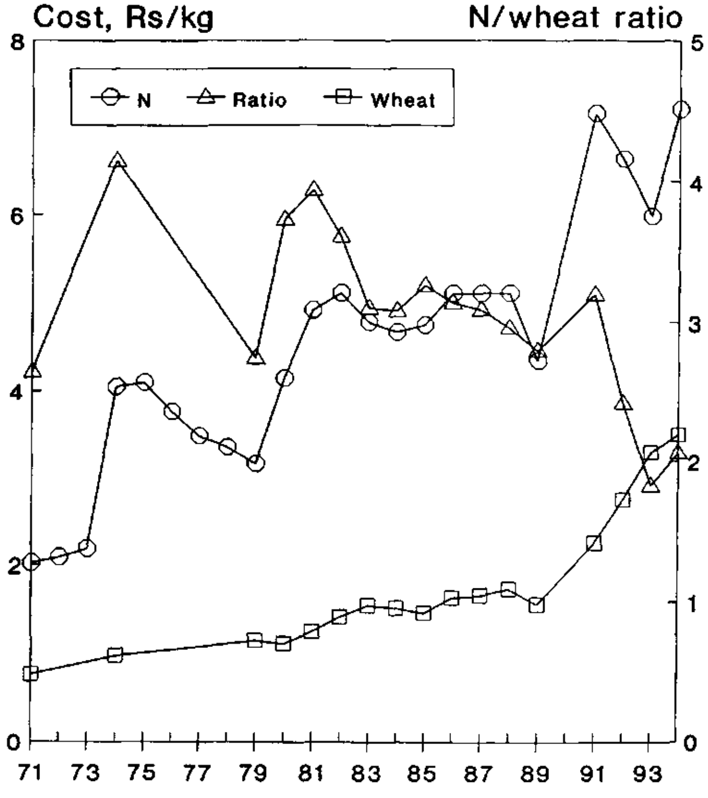

Figure 5.2. Change with time in costs of wheat grain and nitrogen.

Magnitude of yield gap was estimated for fully irrigated districts (>90% irrigated area) of major states. In such districts of U.P. optimal economic yield was 5.32 t ha^{-1} and actual yield was only 2.47 t ha^{-1} indicating a yield gap of 2.84 t ha^{-1}. This yield gap if bridged can result in additional production of 8.64 Mt (Table 5.3). Yield gap is rather low (1.2 - 1.3 t ha^{-1}) in most districts of Punjab and Haryana but nevertheless closing this gap can result in additional production of over 5 Mt. There is a large yield gap of over 3.0 t ha^{-1} in Rajasthan. Bridging the yield gap in other districts where irrigation potential is relatively lower provides sufficient opportunities to meet future demands. As pointed out earlier as well, these yield gaps were obtained from optimal economic yields in a no constraint environment. Consideration of factors such as limited and timely availability of irrigation, cropping pattern, access to credit and other services, availability of other inputs would reduce optimal economic yield levels and thus yield gap. There is a need to understand principal factors that cause these yield gaps.

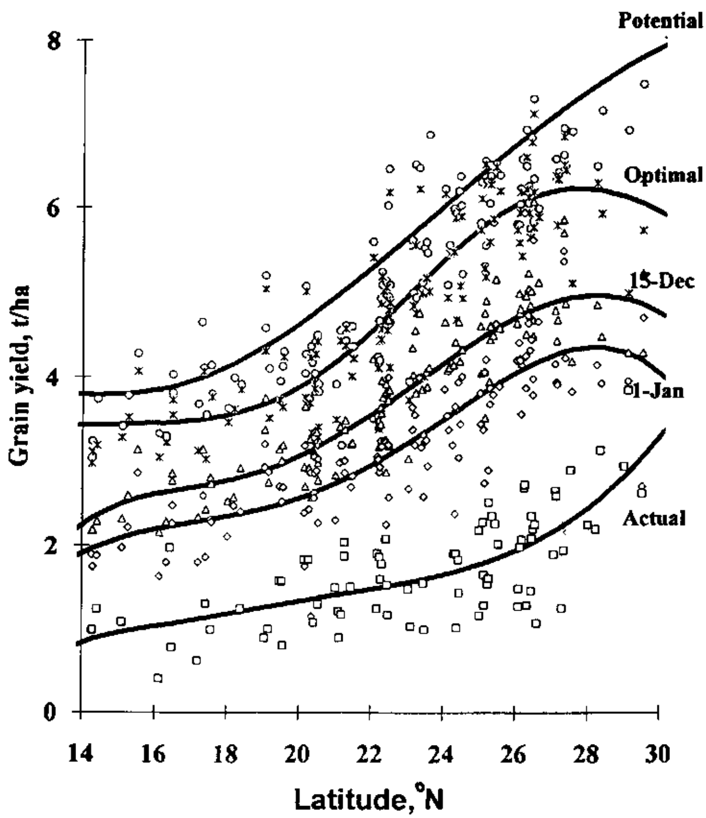

Figure 5.3. Potential, optimal economic and actual grain yields of wheat as a function of latitude. Also shown are the simulated yields on 15 December and 1 January sowings to illustrate the contribution of late sowing to yield gap.

Table 5.3. Magnitude of yield gap in irrigated districts. Only those districts where 90% or more wheat area is irrigated are considered. Optimal economic yields and yield gaps would generally be lower than those shown here if the limitations due to frequency and timing of irrigation availability and biotic factors are also considered. See text for more details.

State	No of districts	Area	Current		Optimal economic		Gap	
			Yield	Production	Yield	Production	Yield	Production
		m ha	t ha^{-1}	Mt	t ha^{-1}	Mt	t ha^{-1}	Mt
U.P.	18	3.04	2.47	7.53	5.32	16.2	2.84	8.64
Punjab	9	2.72	3.76	10.23	5.02	13.66	1.26	3.43
Haryana	12	1.82	3.41	6.20	4.70	8.55	1.29	2.35
Rajasthan	11	0.52	2.42	1.26	5.48	2.85	3.06	1.59
Gujrat	4	0.05	2.40	0.12	4.60	0.23	2.20	0.11
Others	21	0.11	1.45	0.16	2.20	0.24	0.75	0.08
India	75	8.26	3.09	25.5	5.05	41.7	1.96	16.2

Principal Causes of Yield Gap

Date of Sowing

Experimental studies as well as simulation results indicate that the first fortnight of November is the optimal time for wheat sowing (Chapter 4). But a large proportion of farmers sow wheat much after the optimal time. In U.P. and Bihar, a large proportion of farmers sow as late as December and January (WPD, 1989). A major reason of this delay is that wheat is now being grown after rice, which matures in October - November. Simultaneously, there is often a long turn-around period. Chapter 4 has shown that wheat yields are reduced if sowing is delayed beyond the optimal time (November 15). Since rice, the crop preceding wheat in many districts is generally more remunerative, farmers try to maximize its yield. Thus, even if wheat sowing gets delayed they make more profit from the cropping pattern.

The magnitude of yield gap that can be explained by date of sowing alone can also be gauged from Figure 5.3. It is evident that almost 35 - 50% of the gap could be ascribed to sowing date effects. As much as 1.5 t ha^{-1} gap could be explained by one month's delay in sowing. In particular at higher latitudes a large proportion of the yield gap was explained simply by sowing date effects. In middle latitudes considerable area is unirrigated and therefore, a greater number of factors cause yield gap.

Irrigation

The dramatic increase in yield over the last two decades, particularly in north-western regions of the country, was associated with enormous change in input structure. There was an intensified use of inputs particularly of irrigation, fertilizers and pesticides. During the last 25 years, percentage of irrigated wheat area has increased from 35% to 75%. But not all areas classified as irrigated receive optimal irrigation amount at recommended stages. In western U.P., for example, although general recommendation is 5 - 6 irrigations only a limited area receives more than three irrigations (Sinha et al., 1985). On the other hand in some other parts where both canal and groundwater are freely available, such as in Punjab, there is a tendency to over- irrigate because irrigation constitutes only a small portion of the total farm expenditure. Recent compilation of data shows that Punjab farmers spend only 5.8% of their total operational costs on irrigation whereas Haryana and U.P. farmers spend 10-12% (Anonymous, 1991a). Such trends in availability and cost of irrigation cause significant effects on use efficiency of other inputs and result in decreased yields and large yield gaps.

Irrigation availability greatly affects N response. Aggarwal and Kalra (1994) found considerable interactions between climatic variability, irrigation availability and fertilizer response. These interactions were particularly pronounced at low levels of input (irrigation and N) usage such as in eastern U.P., Bihar and M.P. This has important implication. At low levels of water availability it is difficult to decide optimal levels of N fertilizer for maximizing yield returns in view of uncertainty of response until late in the season. This may also explain farmers reluctance to apply N to optimal levels indicated by simulation due to uncertainty of weather, availability of irrigation and hence returns to fertilizer use.

Nutrients

Consumption of inorganic fertilizers has increased over time in all wheat producing regions. Simultaneously there is a distinct decline in the amount of organic matter applied. There is large inter-state and intra-state variation in fertilizer use (Figure 5.4). The NPK application to wheat has crossed 200 kg ha^{-1} level in Punjab whereas it is only about 100 kg ha^{-1} or less in states of U.P. and Bihar. In Rajasthan most farmers apply 10 - 15 kg ha^{-1} fertilizers to wheat. The application of nutrients varies a lot within most states. In general, in most states only 50% or less farmers apply recommended dosages (WPD, 1989). Such suboptimal application of nutrients, often even in well irrigated areas, despite a favourable price ratio causes large yield gaps. On the other hand, there are few districts in Punjab where farmers apply more than optimal or recommended dosage (generally 120 - 150 kg N ha^{-1}).

The response of crops to N also depends on timely availability of irrigation, other nutrients and access to cash or credit to purchase inputs. At many places such as in eastern India, the farmers capacity to purchase inputs is limited. Credit facilities at such places are also limited. Subsidies on phosphatic and potassic fertilizers were recently reduced by the Government. This resulted in sharp increase in their prices and consequent reduction in their application. This imbalanced application will affect crop response to other nutrients including N and thus reduce optimal economic yields. Current price ratios of grain and N fertilizer are encouraging farmers in areas such as Punjab where input use is very high to apply more N to perhaps cover up the inefficiencies in the use of other inputs. This is very likely to increase problems of N leaching due to reduced N uptake efficiency at high N application rates and thus gradual deterioration of environment. Policy interventions are needed.

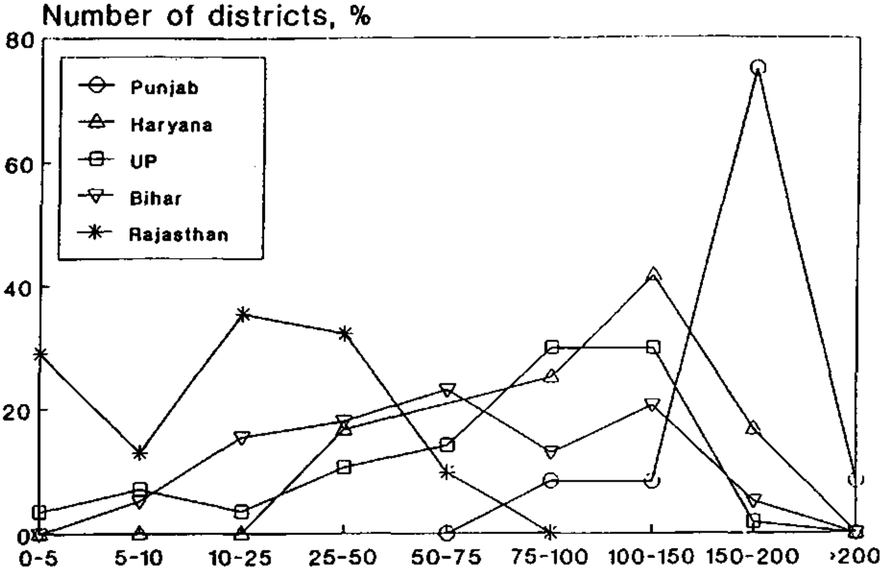

Figure 5.4. Variation in the level of NPK use in different states (Source - FAI, 1990).

Conclusions

Crop growth simulation models together with existing databases of physical, biological and socio-economic attributes, geographical referencing and optimization techniques can help in setting up information systems that can be used for a number of applications. Such systems allow us to estimate crop production potentials, yield gaps, resource requirements for different agricultural strategies, assess potential environmental impacts, generate thematic maps and tables, and thus help in productivity related agro-ecological characterization. The methods presented in this chapter quantitatively analyse the agro-ecological properties of different land evaluation units in terms of biophysical and socio-economic factors, and their interactions and provide us an instrument to understand potentials, constraints and opportunities for agricultural development. Regions with greater potential for yield increase with a given amount of input can be identified. For example, results indicate that optimal economic yields in Punjab and U.P. state are similar and larger yield gaps in most districts of U.P. state are due to suboptimal input use and late plantings. Relatively small yield gap in Punjab indicates that research there must now focus on increasing yield potential and input use efficiency. Results based on single commodity analysis however may have limitations. In Indo-gangetic plains, most wheat is grown after rice. The latter fetches higher price and thus even if wheat sowings get delayed farmers make more profits per year. There is a need to analyse crop production and profits over whole farm which farmers try to maximize.

Once databases are stored in a GIS system, this methodology can rapidly generate new agro-productivity zones, or modify old ones as new concepts or technology such as new varieties become available. The databases and GIS can also be used to store spatial and temporal inventory of regional data on yields, fertilizer application practices and other input usage for ready and easy reference. The analysis done for this chapter had limitations in terms of availability of precise databases, for example, on costs of grain and N, and soil physical characteristics in different regions. There is an urgent need to develop high quality databases relating to different aspects of agro-environment. The Government of India has recently set up database centers in each district to collect primary data on soils, weather, land use and crop productivity besides other activities such as urban development, education, water resources and health. These centers are connected via a satellite network, NICNET, based in New Delhi. Such databases will be extremely useful for strategic and tactical decisions relating to eco-regional development.

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6. Effect of probable increase in carbon dioxide and temperature on wheat yields in India

Abstract

Effect of increase in carbon dioxide and temperature on growth, yield and water use of wheat was simulated for several locations of India using dynamic crop growth model-WTGROWS. Long term average weather and average soil properties for various agro-ecological zones were used. The effect of climatic change on productivity was dependent upon the magnitude of temperature change. At 425 ppm CO_2 and no rise in temperature, a 1°C rise in mean temperature had no significant effect on potential yields but irrigated and rainfed yields increased at most places. An increase of 2°C in temperature reduced potential grain yields at most places. The effect on irrigated and rainfed productivity varied with the location. The natural climatic variability also had considerable effect on the magnitude of response to climatic change. Evapotranspiration was reduced in irrigated as well as rainfed environments. The responses to climatic change were closely related to effects of increased temperature on crop duration.

Introduction

Wheat is an important cereal crop of India and is grown from 15°N to 32°N, from 72°E to 92°E and from sea level to fairly high altitudes. Wheat crop season extends from late October to early May. Since wheat is grown at widely varying latitudes, the crop experiences different temperatures during the crop season. The mean temperatures during crop season are 16°C in northern region, 20°C in eastern and 23°C in central and peninsular India. Due to intensive cropping practiced in most irrigated areas, a large proportion of wheat is sown later than the optimal time. Due to this delay, grain-filling period occurs in relatively higher temperatures. These climatic differences associated with location together with annual variation in climatic parameters strongly effect growth and productivity of wheat.

Lately, there has been a serious concern about the possibilities of a climatic change. It is projected that the ambient levels of carbon dioxide and temperature will rise significantly. For Indian subcontinent, different Global Circulation Models predict an increase of 1 to 4°C in the ambient temperatures (Sinha and Swaminathan, 1991). The level of CO_2 is likely to rise by 2 ppm per year. CO_2 is known to influence photosynthetic processes whereas temperature influences all aspects of crop growth, development and water and nutrient use (Baker and Allen, 1993). It can, therefore, be expected that climatic change will have significant interactions with crop production. Both positive and negative effects of climate change on agriculture have been projected depending upon the crop, input use and region (Baker and Allen, 1993; Kimball 1993).

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It is important to know how this climatic change would effect growth, development, water use and productivity of different crops in India. Experimentation for such a study is difficult and capital intensive. In this chapter, we have used WTGROWS to estimate the effect of climate change on productivity of wheat in India.

Methodology

Climate change scenarios

Inter-Government Panel on Climate Change of WMO has estimated that CO_2 levels are rising by 1.8 ppmv per year (Houghton, 1991). Mean temperature increase is expected to be 0.3 °C per decade for India. Rainfall is assumed to remain the same during the winter season. Therefore, for 2030 AD, it is estimated that CO_2 level will be 425 ppm and temperature will increase by 1.25 °C over 1990 base values. Temperature increase may be still higher in specific regions while maintaining an average temperature increase of 1.7 °C within the grid (Sinha and Swaminathan, 1991). For the present chapter, we have assumed the climate change scenario for 2030 AD as predicted by IPCC. Since there is uncertainty about the magnitude of temperature rise, analysis has been done assuming a uniform rise in mean temperature of 0, 1 and 2 °C all over India.

Simulation

The methodology followed in this chapter is similar to the one described by Aggarwal (1993). We have used a dynamic crop growth simulation model WTGROWS, developed to describe the effect of various climatic factors and their variability, soil characteristics, agronomic management and physiological factors on wheat growth, development, water and nitrogen use (Aggarwal et al., 1994). The model includes the effect of temperature on all major physiological processes and assumes a 30% increase in the rate of gross photosynthesis and specific leaf weight for the doubling of CO_2. Increase in CO_2 also effects transpiration due to increased resistance to water loss (Penning de Vries et al., 1989). The magnitude of plant responses to higher CO_2 on a long term basis is still under investigation in many laboratories. In the future, these could provide better data for use in the models.

Long-term average monthly weather data of 72 locations spread all over the wheat growing regions of the country were used for the analysis. The daily weather data was estimated by linear interpolation. In addition, daily weather data of 18 years for New Delhi was used for estimating effect of climatic variability on grain yield and evapotranspiration in changed climate. Rainfall during the cropping season is small (50 -100 mm). A representative rainfall distribution was used for the analysis. The geographical distribution of soils was obtained from the agro-ecological zones map of India (Sehgal et al., 1990). In the present analysis, the soil was assumed to be 150 cm deep and at 80% of field capacity at the time of sowing.

The effect of climate change on productivity was simulated for normally sown crops at three levels of production:

1. Potential productivity assuming no effect of water and nutrient stresses on crop growth.

2. Irrigated productivity, assuming application of 120 (80+40) kg N ha^{-1} and five irrigations during the cropping season.
3. Rainfed productivity, assuming no irrigation and 50 kg ha^{-1} basal N application.

The simulations were made for varieties of two maturity classes - early duration (80 - 85 days to anthesis in New Delhi) and medium duration (90 - 100 days to anthesis). The highest yield obtained from these simulations was assumed to be the productivity in that scenario.

Results and Discussion

The potential yields in present weather varied from 2.7 t ha^{-1} to 8.0 t ha^{-1} depending upon the region. The irrigated and rainfed yields were lower and varied from 2.0 t ha^{-1} to 6.0 t ha^{-1} and from 0.5 t ha^{-1} to 4.5 t ha^{-1}, respectively. The effect of climate change on productivity was dependent upon the magnitude of temperature change. Figure 6.1 shows the effect of different scenarios on grain yield of irrigated wheat. At 425 ppm CO_2 concentration and no rise in temperature, grain yield at all levels of production increased significantly at all places.

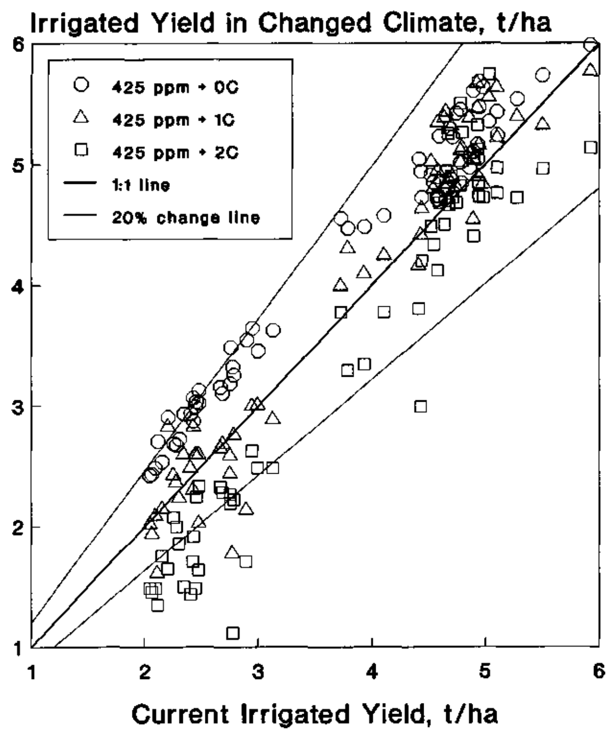

Figure 6.1. Effect of magnitude of temperature increase on grain yields of irrigated wheat in present and changed climate.

A 1 °C rise in mean temperature had no significant effect on potential yields. Irrigated yields, however, showed a small increase in most places where current yields are greater than 3.5 t ha^{-1}. In central and peninsular India, where current irrigated yields are between 2 and 4 t ha^{-1}, the response varied from a significant decrease to a significant increase.

The isolines of simulated irrigated grain yields under current climate and under climate change scenario were plotted for the country (Figure 6.2). There was almost no effect of climate change in northern India but yields were reduced in central India by 10-15%. This reduction in productivity under changed climate unless accompanied with suitable research and policy interventions may reduce wheat production options in central India.

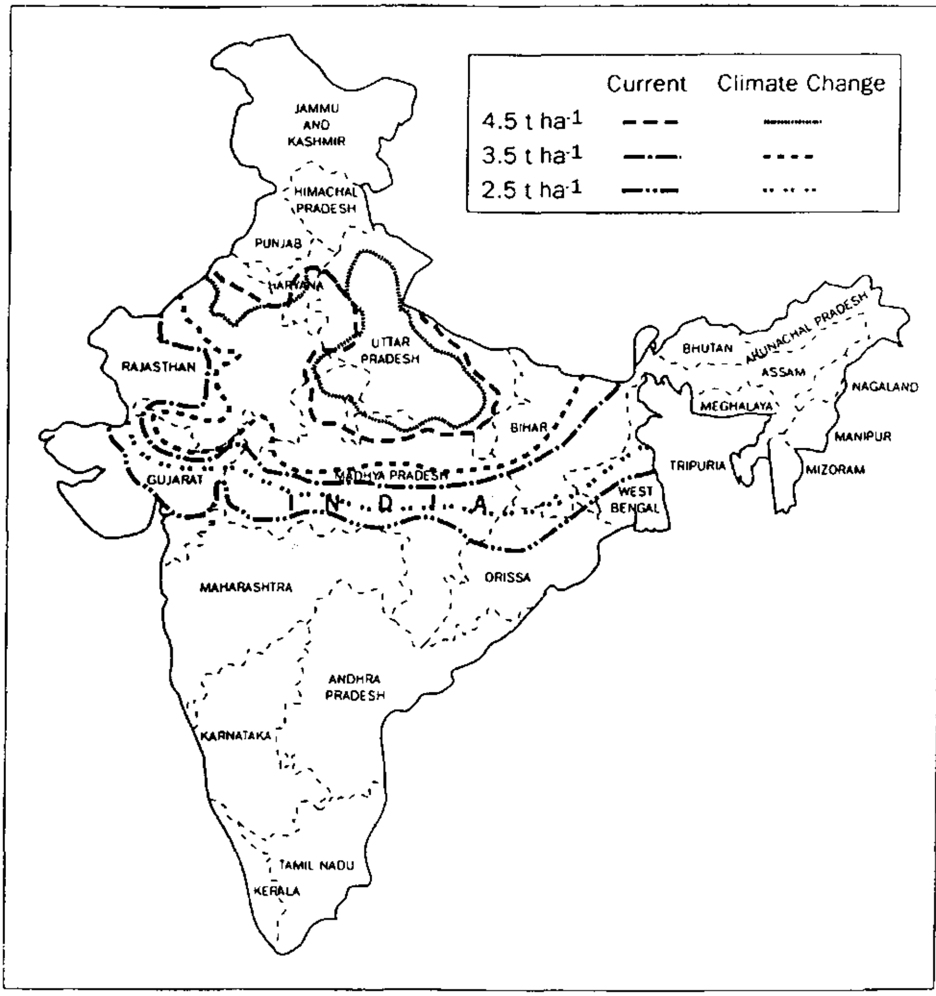

Figure 6.2. Impact of climate change on shift in irrigated wheat productivity zones. Climate change scenario was 425 ppm CO_2 and a 2 °C rise in mean temperature.

Rainfed yields, however, showed a significant increase. An increase of 2 °C in temperature reduced potential grain yields at most places (Figure 6.3). Relatively, for all places where current potential yields are above 5 t ha^{-1}, such as in northern India, the reduction was much smaller compared to places with lower potential productivity. In fact, for a few locations there was a small increase or no significant effect. Table 6.1 shows the mean yields for current and changed climate scenarios according to latitude. In sub-tropical (above 23°) environments there was a small decrease in potential yields (1.5 to 5.8%) but in tropical locations the decrease was 17 - 18%. Irrigated yields were slightly increased for latitudes greater than 27° but were reduced at all other places. The decrease in yield was much higher at lower latitudes. Several locations, particularly where current rainfed yields are greater than 2 t ha^{-1} showed a very significant increase in rainfed yields with climate change (Figure 6.3). These locations are mostly above 27°N; the mean increase here was 28.6% (Table 6.1). Between 25 and 27°N although rainfed yields in current weather are high, there was a significant decrease in changed climate (Table 6.1).

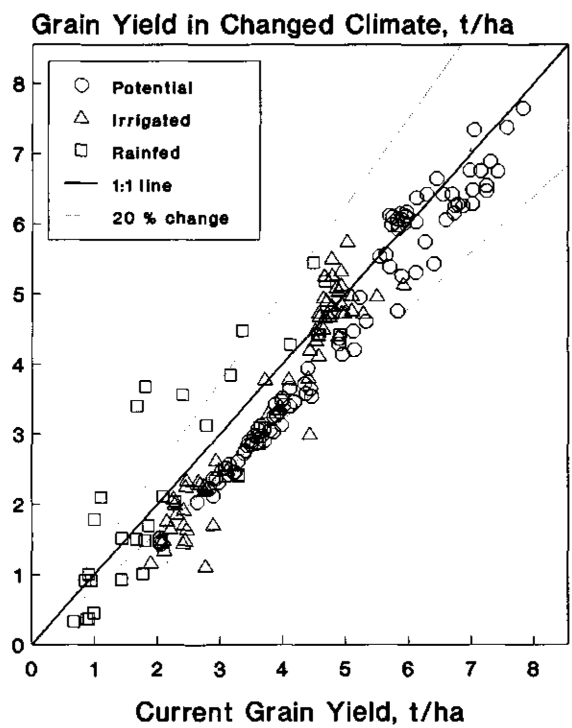

Figure 6.3. Effect of climate change (425 ppm CO_2 and 2 °C increase in mean temperature) on potential, irrigated and rainfed productivity of wheat.

The above results are based on mean long term weather data. The effect of climate change for a location may however vary depending upon the climatic variability. The effect of an increase in CO_2 to 425 ppm and a 2 °C rise in mean temperature was studied on irrigated and rainfed productivity and evapotranspiration for crops sown on 15 November every year for the period 1973 to 1990 using daily weather data. Mean grain yield decreased by 6.2% in irrigated environments and increased by 31% in rainfed environments. However, depending upon the year, irrigated yields in changed climate were higher, the same or less than the current yields (Figure 6.4). Rainfed yields were always higher than the current yields, irrespective of the year.

In all years, climate change reduced evapotranspiration both in irrigated as well as rainfed environments. The mean ET for irrigated and rainfed treatments were 352 and 240 mm in current weather and 302 and 221 mm in changed climate. This reduction in ET, accompanied by CO_2 induced higher growth rates, resulted in considerable improvement in water use efficiency and hence in grain yield.

The above-mentioned results were closely related to the effects of changed climate on crop duration. Depending upon the magnitude of temperature increase, crop duration, particularly the period upto anthesis, was reduced. In northern India, because of this reduction in pre-anthesis duration, grain-filling was often shifted to relatively cooler temperatures of February thus enabling the crop to maintain reasonable grain-filling duration in changed climate. In addition, the improved WUE and growth rates helped the crops to maintain adequate rates of growth. The simulations showed that if the crops are allowed to maintain the same crop duration as in current weather, the effects of climate change are insignificant (data not shown).

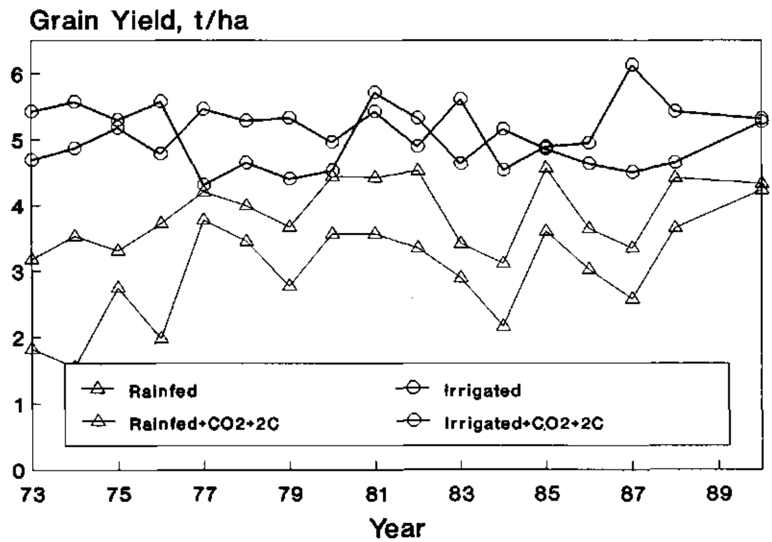

Figure 6.4. Effect of climate change on grain yield of irrigated wheat in different years at New Delhi.

Table 6.1. Grain yield (t ha^{-1}) of wheat in current weather and percent change in response to climate change (425 ppm CO_2, 2 °C increase in mean temperature) in different regions of India.

Region	Potential yield		Irrigated yield		Rainfed yield	
	Current	% change	Current	% change	Current	% change
>27°N	6.66	–3.85	4.89	3.7	2.95	28.6
25-27°N	5.84	–1.54	4.78	–4.4	3.34	–7.2
23-25°N	5.86	–5.6	4.18	–10.76	1.17	–19.6
20-23°N	4.18	–18.4	2.29	–18.3	0.51	–11.8
<20°N	3.69	–17.3	2.43	–21.4	0.97	–23.9

Conclusions

The effect of climate change on wheat productivity is dependent upon the magnitude of temperature change. A one degree increase in temperature throughout the crop season will have no effect or slightly increase productivity in irrigated as well as rainfed environments, particularly in northern India wheat belt. A two degree increase in temperature will reduce potential yields but will have small effect on irrigated yields in northern India. ET will be significantly reduced in changed climate. Relatively, the effect of climate change will be more pronounced in central India where yield potential is already low as a result of relatively higher temperatures. The crop responses to climate change are related to the effect of temperature on crop duration.

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7. Potential and water-limited wheat yields in rice based cropping systems in South-east Asia

Abstract

There is a growing interest in cultivating wheat in south-east Asia for reduction of the drain of foreign exchange and for crop diversification. A crop growth model was used to establish potential and rainfed yields of wheat following rice in different parts of this region. A comparison of measured and simulated yields indicated satisfactory performance of the model. The results indicated that the yield potential of irrigated wheat was between 3.0 and 5.0 t ha^{-1} between 10°S and 23°N latitude at sea level, but it was higher at altitudes between 500-2000 m. Such yields were stable and relatively insensitive to sowing date. Rainfed yields were lower, and have a high year-to-year variability. The gap between potential and water-limited grain yields was small if wheat was sown towards the end of the rainy season on a deep and well- drained soil.

Introduction

In south-east Asia, there is no significant commercial production of wheat. The entire regional demand (4 million ton per year) is met by importing wheat and wheat flour at a huge cost (CIMMYT, 1985). Several countries in this region have had an annual growth in per capita consumption of over 10% annually (Byerlee, 1985). Because of increasing urbanization and changes in dietary habits, the demand for wheat is likely to increase. To reduce the large drain of limited foreign exchange and to increase self-reliance, the governments of most south-east Asian countries have a growing interest in cultivating wheat. Several countries of south-east Asia have become surplus producers of rice and wish to diversify their agricultural production. Since water requirement of wheat is much less than rice, wheat is a logical choice for exploration as a potential crop for the dry season. The national plant breeding programmes as well as the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) have initiated varietal improvement programmes to develop wheat varieties adapted to specific environments in this region.

Preliminary agronomic experiments to determine the yield potential of wheat have been conducted in Thailand, Philippines, and Indonesia. The presently available varieties yield 2 tha^{-1} or more in irrigated conditions (CIMMYT, 1985; Aggarwal et al., 1987). The rainfed yields varied depending upon the region and the year. Wheat being a crop from temperate and subtropical regions, one might wonder whether such yields were the best that can be

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attained in a region where the environment was predominantly humid, daylengths were always more than 11h, and temperatures were above optimal for wheat. Before attempting to introduce a new crop, it is also desirable to have more knowledge about its long-term performance. For example, is the wheat crop calendar compatible with the local cropping systems which are predominantly rice based? Given the yearly climatic variation, what will be the risk associated with growing wheat?

Crop growth models are useful tools to quantify the environmental limits to crop production. Their application minimizes the requirement for costly and lengthy experimentation (Loomis et al., 1979). For this chapter, a crop growth simulation model was used to establish the potential and rainfed yields of wheat following rice in south-east Asia between 23° North and South of the equator and between 94° and 145° East of Greenwich for elevations up to 2000 m.

The Model

The model used was WTGROWS (Chapter 2). The thermal time needed between seedling emergence and anthesis was calibrated till the duration was similar to that of UPLW-2, a variety released for cultivation in tropical Asia by the Philippine Seed Board. Other genetic parameters were assumed to be same as that of a standard semi-dwarf cultivar (Chapter 2). In tropical environments of SE Asia, heavy rainfall can cause water logged conditions that reduce the growth of the wheat crop particularly when seeding occurs at the end of the wet season or when the dry season brings unexpected rains. The effect of short periods of water logging (up to 10 days) on wheat yield is small (Luxmoore et al., 1973), and this phenomenon was not considered here. The rainfed wheat yields may be higher than our simulations indicate when groundwater contributes to crop water uptake. This situation is probably not uncommon in rice soils. These limitations need to be eliminated before the model is applied to generate-detailed results for specific situations. However, we do not expect these limitations to have a major effect on yield levels, yield trends or yield variability as discussed under 'Results' and 'Conclusions'.

Weather

The climate of south-east Asia is classified as humid tropics. The region is not climatically homogeneous (Oldeman and Frere, 1982). Nearer to the equator, temperatures are higher, at similar elevations, and daylength is less variable.

The agroclimate in this study was based on latitude and elevation. The monthly weather data sets for 147 meteorological stations located below 200 m elevation in Indonesia, Philippines, and Thailand, three important countries of the region, were obtained from the IRRI agroclimatic data bank (the original source of much of the data was the World Meteorological Organization). These stations were clustered into six groups of latitudes: 10°S to 5°S, 5°S to equator, equator to 5°N, 5°N to 10°N, 10°N to 1 5°N, and 15°N to 20°N. Long-term mean data for Kapurthala, India (30°N), was included for comparison. The monthly mean solar radiation and maximum and minimum temperatures were determined for each group and used as the driving variables in the model. The weather variables for any given latitude were estimated by linear interpolation. The groups up to 10°N were fairly homogeneous but the variability within the group increased with more northerly latitudes. In general, Philippines stations have slightly higher temperatures than those in Thailand.

For climatic data at higher elevations, data sets were available for several locations in Indonesia, but not for Philippines and Thailand. Oldeman and Frere (1982) derived a relationship of maximum and minimum temperatures with elevation. To establish the trends in potential yields at higher elevations, this relationship was assumed to be valid for all of south-east Asia (although this results in small deviations from the actual data for some locations). Solar radiation in humid south-east Asian tropics decreases with elevation due to increasing cloud cover (Oldeman and Frere, 1982). We summarized and simplified their results by assuming that the radiation decreased linearly with elevation by 25% between sea level and 2000m elevation.

To establish the stability of the crop, the model was run for 25 different years. In one situation (Los Baños) a historic weather record was available. In the other case, 25 years of data were generated on the basis of 3 years of historic data (Supit, 1986).

Results and Discussion

Model evaluation

The model's performance has been evaluated in several tropical and sub-tropical regions (Chapter 2). The irrigated, well-fertilized experiments described by Aggarwal et al. (1987) and Aggarwal (unpublished) in Los Baños, a typical tropical location, were used to evaluate the changes made in the model. Crop growth under optimal conditions was simulated for several sowing dates within a crop season as well as in different seasons at the same location. Figure 7.1 shows that most points were on the 1:1 line or close to it, indicating that the model's performance was satisfactory for our purpose. The largest discrepancy (simulated 2.3 *vs.* observed 1.2 t ha^{-1}) occurred in 1983 which had the highest temperature. The low observed yield was probably due to more rapid senescence in the field crop than was simulated, but (unplanned) water stress might also have been present.

An evaluation of the crop-water balance model could not be performed for any location in south-east Asia since no data set with detailed measurement of soil water was available. A few experiments were done earlier at Los Baños to study the effect of water availability on wheat grain yield (Aggarwal et al., 1987), but no quantitative information was collected on the soil texture, water holding capacity or the moisture content at sowing time. In some cases, soil properties of the adjacent and apparently similar fields were available. To simulate these irrigation experiments, we assumed that the field had the same soil and that it was at field capacity at seedling emergence. Since the fields were deep-tilled before sowing, the maximum rooting depth was assumed to be 1.2 m. Actual daily weather data were employed. In two out of four simulated experiments, the difference between predicted yields water-limited and observed yields was less than 5%. In the third experiment, simulated yields were lower by 23% than the actual yields, whereas in the fourth, yields were higher by 30%. These discrepancies were, possibly, due to inadequate characterization of the soil of the experimental sites.

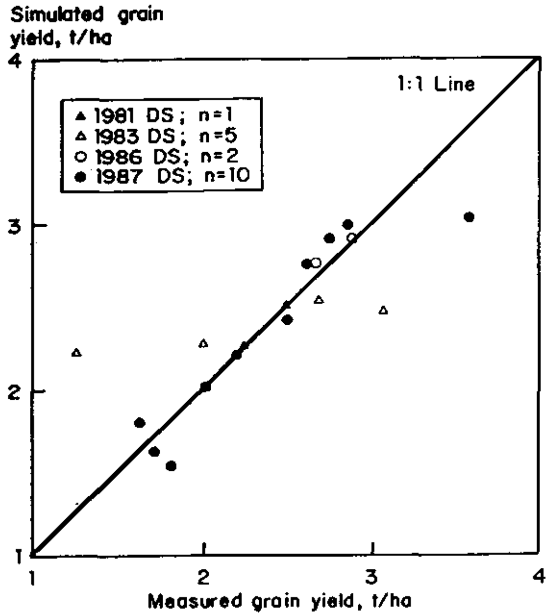

Figure 7.1. A comparison of measured and simulated grain yields of wheat grown at Los Banos, Philippines. Crops were grown on various sowing dates in 1981, 1983, 1986 and 1987 dry seasons (DS).

Potential grain yields at different latitudes and elevations

The growth of wheat was simulated for the latitudes 7°S, 0, 7°N, 14°N, 21°N, and 28°N at 0, 500, 1000, 1500 and 2000 m elevation, respectively. The sowing date was assumed to be 25 June for 7°S, 25 December for the equator, 7°N and 14°N, and 15 November for 21°N and 28°N latitudes. These were optimal planting dates, as is shown later. The simulated potential grain yields varied between 2.8 and 11.0 t ha^{-1}. Potential grain yield increased with the latitude and elevation. Grain yields at southern latitudes were higher than at similar latitudes on the northern side of the equator.

To facilitate analysis of the simulation results, the following relation between simulated grain yields (GY, kg ha^{-1}), latitude (LAT, degree) and elevation (ELV, m) was established:

$$GY = 3005 - 66.8LAT + 7.36LAT^2 + 2.62ELV \quad (R^2 = 0.93^{**})$$

From this equation, isoquant plots were constructed (Figure 7.2). The grain yield potential in south-east Asia exceeded 3.0 t ha^{-1} almost everywhere. At sea level, grain yield was 3.0 t ha^{-1}

between 0 and 8°N latitude, and it increased to 5.0 t ha^{-1} at 21°N and 4.5 t ha^{-1} at 10°S. Grain yield potential increased with elevation at all latitudes. At 500 m elevation, the estimated grain yield potential was more than 5.0 t ha^{-1} for latitudes below 5°S and above 15 °N of the equator. The potential exceeded 6.0 t ha^{-1} at 21 N and 5.7 t ha^{-1} at 10° S. At 1000m elevation, the grain yield was 5.8 tha^{-1} between 0 and 10°N latitudes, and it increased up to 7.6 t ha^{-1} at 21°N.

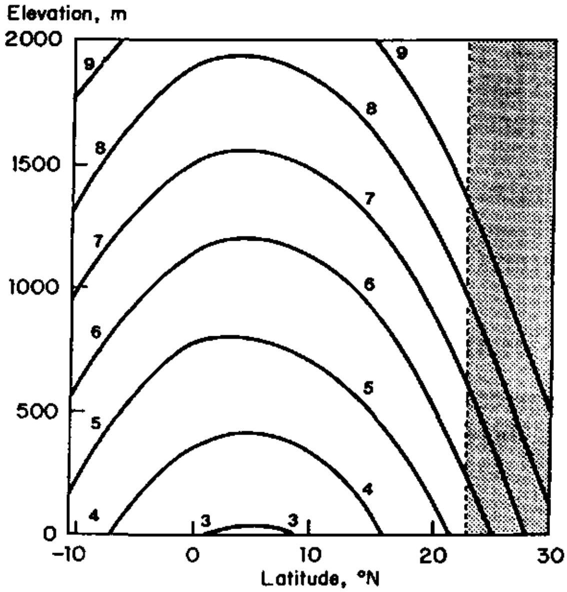

Figure 7.2. Isoquant (equal yield) lines of simulated grain yields in Southeast Asia expressed as a function of latitude and elevation. Shaded portion is outside Southeast Asia but is included for comparison. Numbers on the lines are yields in t ha^{-1}.

The potential yield was calculated to exceed 8.5 t ha^{-1} depending upon the latitude, as the elevation increased to 2000 m. The main cause of the large response to elevations was the decline in temperature which more than compensated for the lower light level at higher elevations (sensitivity analysis showed yield to be almost proportional to light level in the conditions of this study). However, the CO_2 concentration in the air at 1000 and 2000 m elevation is 12 and 22% less, respectively, than at sea level. This leads to a reduction in the rate of photosynthesis and consequently to a reduction in yield. This reduction was not included in the model. Grain yields as determined with this program were, therefore, probably 3% and 7% too high at 1000 m and 2000 m, respectively.

The regression equation was also used to estimate potential yield for a few locations in India where wheat is a common crop. The estimated potential yields for Coimbatore (11°N, 409 m elevation), Indore (22.4°N, 567 m elevation) and New Delhi (28.3°N, 216 m elevation) were 4.2, 6.7, and 7.6 t ha^{-1}, respectively. Such yields were indeed obtained in well-managed experimental trials at these stations (Bhardwaj et al., 1975), providing further confidence in the model.

The above simulated potential grain yields (kg ha^{-1}) were related to the maximum (Tmax) and minimum (Tmin) average February temperature (August temperatures for southern latitudes) by the following regression equation:

$$GY = 15\,411 - 310.6\ Tmax - 115.38\ Tmin\ (R^2 = 0.89^{**})$$

The February temperature was chosen because flowering occurs generally in this month. From this equation, isoquant plots of grain yield were constructed as shown in Figure 7.3. When the maximum temperature was between 25 and 35 °C and the minimum temperature between 15 and 25 °C, a situation common in many lowland locations in south-east Asia, the potential grain yield was between 1.8 and 6.0 t ha^{-1}.

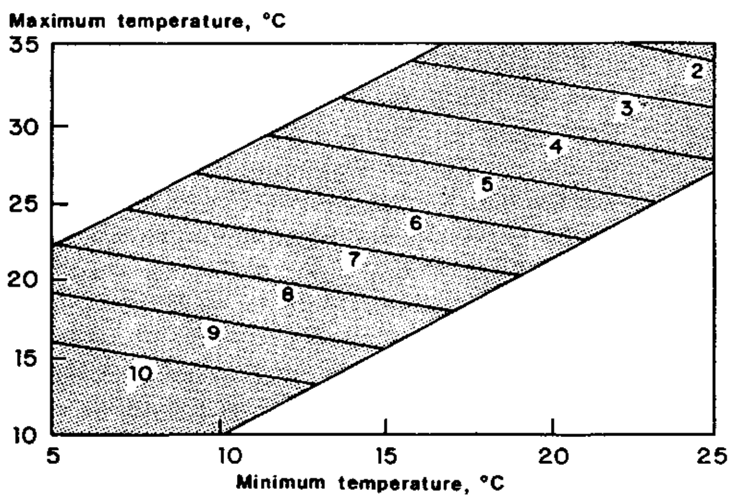

Figure 7.3. Isoquant (equal yield) lines of simulated potential wheat yields as a function of mean maximum and minimum temperatures (August for southern latitudes). Numbers on the lines are yields in t ha^{-1}.

Effect of date of sowing on potential grain yield

It is commonly observed in south-east Asia that sowing of dry season crops is delayed due to either delayed planting of rice, the most common wet season crop, or use of long duration photosensitive rice varieties, or a long turnaround time. The effect of sowing date on wheat growth and yield was simulated at 7°S, 0, 7°N, 14°N, 21°N and 28°N latitudes at sea level for crops sown at 15 day intervals starting 15 October (15 April at 7°S) and until 30 January (30 July at 7°S). The grain yields calculated for the various sowing dates at different latitudes were shown in Figure 7.4. These dates of sowing had very little effect on grain yield between 7°S and 7°N latitudes. At 14°N as well as 21°N, grain yields were insensitive to sowing dates between 15 October and 15 December. The yield decreased by 11 kg ha^{-1} day^{-1} at 14°N and by 20 kg ha^{-1} day^{-1} at 21°N for later sowings.

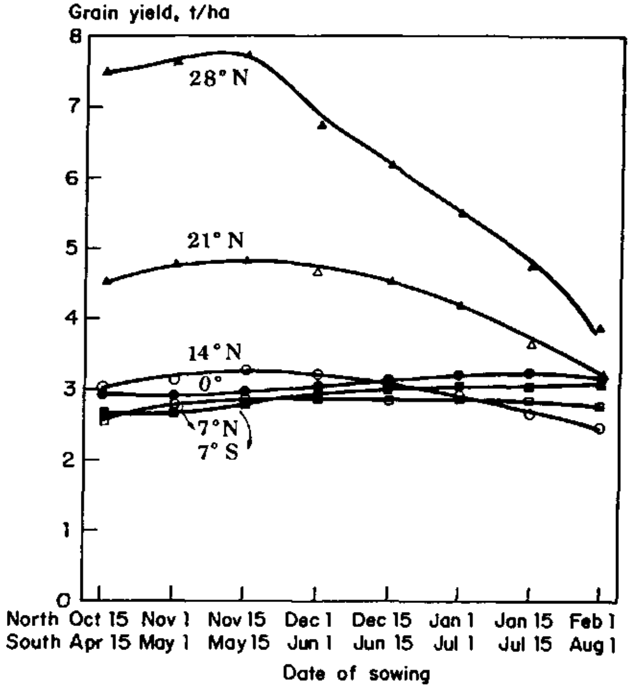

Figure 7.4. Effect of date of sowing on simulated potential grain yields at sea level for a range of latitudes.

By comparison, at 28°N, a sub-tropical location, the effect of date of sowing was very pronounced. The optimal date of sowing was between 15 October and 15 November and for every day's delay in sowing, grain yield was reduced by 50 kg ha^{-1}. Such a sharp decrease at higher latitudes is well documented (Bhardwaj et al., 1975; Hobbs, 1985).

In intensive cropping systems, there is always a premium on high yielding and yet shorter duration crops. The currently available wheat varieties generally mature in 75 to 90 days at lower elevations in south-east Asia, whereas at higher elevations such as 1000 m, they mature in 100 - 110 days. These durations were comparable and often shorter than those of other cereal crops.

Stability of potential grain yield

An important aspect in evaluating the suitability of a crop is the stability of its performance over the years. In this chapter, yield stability refers to the difference in yield levels that have a probability of 75% and 25% of being exceeded in any year; the smaller the difference the larger the stability. To quantify stability, the growth of wheat in Los Baños (14°N) sown at 15-day intervals between 15 November and 30 January was simulated using actual daily weather data of 25 years. The year-to-year variations in grain yield for 15 December and 1 January sowing dates were plotted in Figure 7.5. The potential grain yield fluctuated between 2.3 and 3.4 t ha^{-1} for both sowings. It was interesting to observe that the grain yields after 1977 were, on an average, lower than before this date. Examination of weather data showed that the recorded mean maximum temperature in the post-flowering period (February - March) during the last 10 years was higher than earlier years. This illustrates again that when water supply was optimal, the wheat crop in the tropics was very sensitive to changes in temperature.

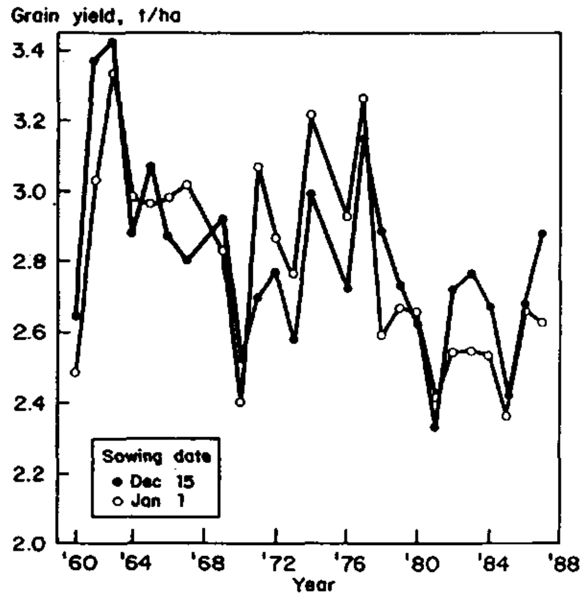

Figure 7.5 Year-to-year variation in simulated potential grain yield of wheat in Los Banos, Philippines on 15 December and 1 January.

A frequency distribution analysis of grain yields of such a sequence of years provides the probability of obtaining a certain grain yield for specific sowing dates. This was done for the period 1 September to 15 January for two locations: Sanpatong (18.4°N, 320 m elevation, Thailand, a relatively cool location with moderate rainfall during wet season and no rainfall during dry season) and Los Baños (14.1°N, 20 m elevation, Philippines, warm, heavy rains in wet season, limited rainfall in dry season). The maximum grain yield at almost all probability levels was obtained for wheat sown on 1 January in Los Baños and on 1 November in Sanpatong (Figure 7.6). Yield variability was less in Sanpatong as compared to Los Baños due to fewer cloudy days in the crop season in Sanpatong. The closeness of the lines for 1 December, 1 January, and 15 January sowing dates in Los Baños and 1 October, 1 November and 1 Deeember in Sanpatong again indicated a period of 30 - 50 days at lower latitudes during which wheat yields were not affected by date of sowing. For the optimal sowing dates at 75, 50, and 25% probability levels, grain yields were 2.7, 2.8 and 3.1 t ha^{-1} in Los Baños and 3.9, 4.1 and 4.2 t ha^{-1} in Sanpatong. The small differences between these probability levels suggest that wheat yields will be fairly stable in irrigated and well-managed field conditions in south-east Asia.

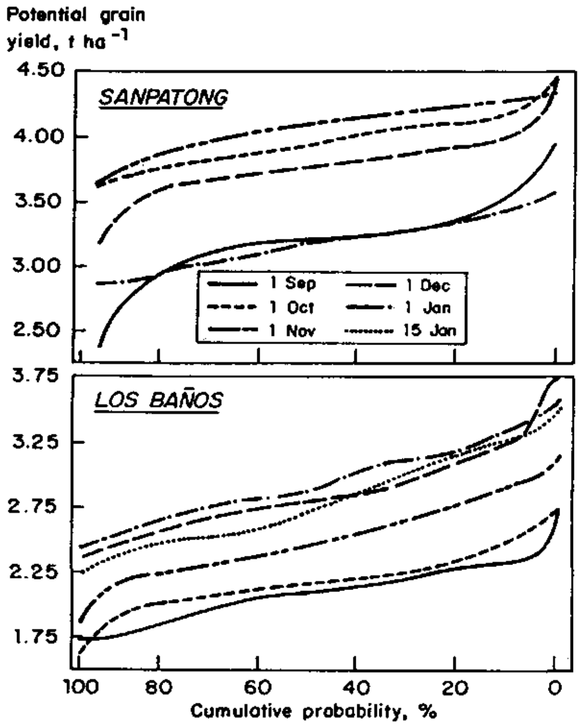

Figure 7.6. Effect of date of sowing on cumulative yield probabilities of wheat grown in Los Banos, Philippines and Sanpatong, Thailand. Curves are based on 25 years of simulated yields.

It was concluded that the yield potential of current wheat varieties was 3.0 to 5.5 t ha^{-1} in south-east Asia, and that it was fairly stable over years. The yield potential increased with elevation. Delayed wheat sowing will have little or no effect on the grain yield of irrigated wheat. Since the crop duration was less than 3 months, wheat can fit very well in intensive cropping systems. There are 4.1 M ha of dry season, irrigated rice areas in south-east Asia, mainly north of 1 5°N latitude and south of 5°S latitude (Huke, 1982a). As shown in Figure 7.2, the yield potential of wheat in these areas was above 4.0 t ha^{-1}. From a purely agronomic viewpoint, these areas are suitable to cultivate wheat.

Water-limited wheat yields

The effect of sowing date on rainfed wheat was simulated for Los Baños and Sanpatong. The comparison was made for wheat grown on a 1.2 m deep light clay soil which allows 1.0 m rooting depth. The growth was simulated for crops planted at 15-day intervals starting 1

September. At both locations, runs were made for 25 years. The average yield and standard deviations are presented in Figure 7.7.

The potential yield (no water deficit) at Sanpatong was about 4.0 t ha^{-1} for sowing between 1 October and 15 November and decreased in later sowings to 2.8 t ha^{-1} by 15 January (Figure 7.7). The grain yield of rainfed wheat, however, was sensitive to sowing date. The maximum rainfed yield was 2.7 t ha^{-1} for sowing between 1 September and 1 October. The grain yield decreased sharply subsequently. It was concluded that in Sanpatong and similar locations, 2.5 t ha^{-1} grain yield could be obtained when sowing was completed before 5 October.

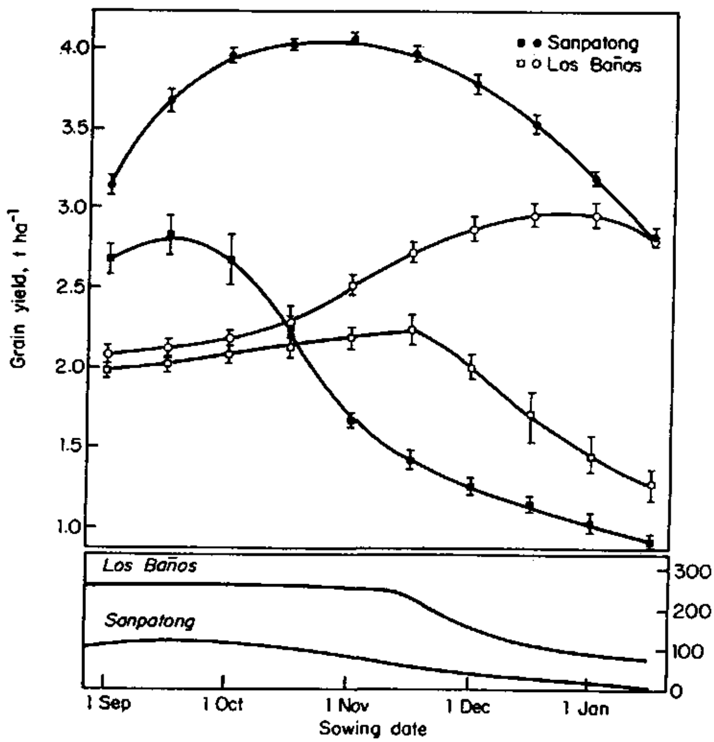

Figure 7.7. Effect of sowing date on water-limited wheat yields and its standard deviation in soils ( ) in Sanpatong (Thailand) and Los Banos (Philippines). Also shown are the potential yields (O) and monthly rainfall.

By comparison, at Los Baños, the potential grain yield was between 2.7 and 3.0 t ha^{-1} for sowing between 15 November and 15 January (Figure 7.7). The rainfed wheat yields were around 2.0 t ha^{-1} when sown on or before 1 December.

Although the potential grain yield was 1.0 t ha^{-1} higher in Sanpatong than in Los Baños, the maximum rainfed grain yields differed by only 0.5 t ha^{-1}. Due to significant rainfall in the dry season in Los Baños, the delayed planting of wheat caused less reduction in grain yield than in Sanpatong. The dry season rainfall was common at several locations in south-east Asia (Huke, 1982b; Oldeman and Frere, 1982). It was important to note that though the potential grain yield at these lower latitudes was less, a large part of this could be realized without irrigation. It will be essential to establish the wheat crop as early as possible to take advantage of the stored soil water and dry season rainfall.

Stability of rainfed yields

The year-to-year variation in rainfed yields was determined for wheat sown on 1 December at Los Baños for the 25 years. Because soil texture and rooting depth of the ricelands vary a great deal (De Datta, 1981), three representative rice soils were considered: heavy clay, light clay, and loam. It was assumed that the texture was uniform for the whole profile. Maximum rooting depth was either 0.25, 0.5, or 1.0 m to mimic the presence of a root impeding layer at different depths. The fraction extractable water was 13, 18 and 25% as was common for heavy clay, light clay, and loam soils, respectively (Driessen, 1986).

Frequency distribution analysis of wheat yields showed that when the maximum rooting depth was 0.25m, grain yields were very low and highly unstable, irrespective of the soil texture (Figure 7.8). This occurs in many rice soils with a compacted layer. In many years, no grain yield was produced since the crop died before flowering. When the soil allowed a rooting depth of 0.5 m, there was a 50% probability of harvesting 0.6, 1.0, and 1.2 t grain ha^{-1} in heavy clay, light clay, and loamy soils, respectively. These yields were less variable than those at 0.25 m rooting depth (Figure 7.8). With a maximum rooting depth of 1.0 m, the expected grain yields (50% probability) were 1.5, 2.0, and 2.3 t ha for heavy clay, light clay and loam soils, respectively.

The duration of a crop can be important in water-limited situations. It is recognized that early maturity is a common mechanism for avoiding drought in several crop plants (Begg and Turner, 1976; Fischer and Turner, 1978). Upon decreasing the pre-anthesis duration of wheat crop by one week by increasing the rate of pre-anthesis development, simulated yields were, in general, higher by 0.2-0.3 t ha^{-1} (results not shown). The relative effect was more pronounced when the maximum rooting depth was shallow.

This model predicted that the gap between potential yields and rainfed yields was small when wheat was planted on a deep soil that was at field capacity. The latter condition can be ensured in the optimal planting period by not delaying wheat sowing once the rains have reduced and any waterlogging has disappeared. Simultaneously, if the soils were deep, relatively light textured and free of root restricting layers, yields were fairly high and often close to the potential level. The irrigation requirement would not be large, at least on such deep soils. In field experiments there was little response to more than 2-3 irrigations (Aggarwal et al., 1987).

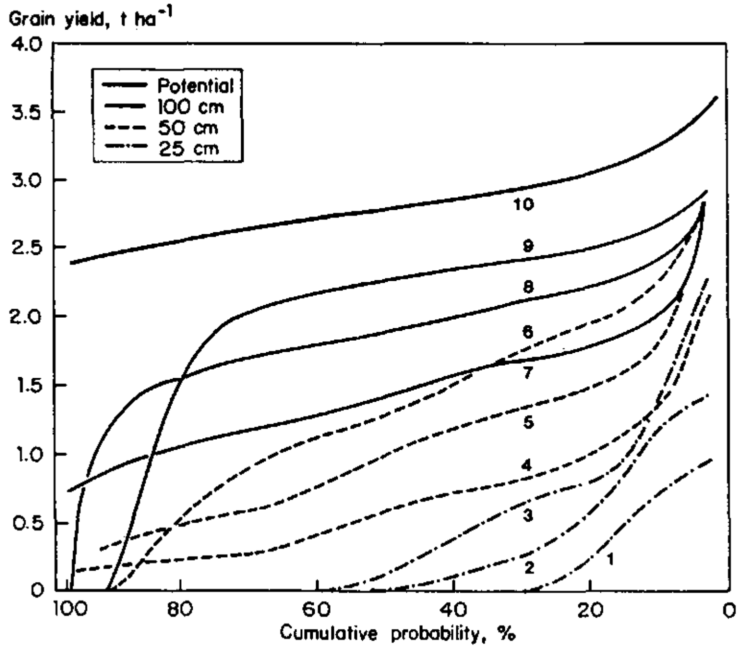

Figure 7.8. Effect of soil depth and texture on cumulative yield probabilities of rainfed wheat sown on 1 December at Los Banos, Philippines. Lines 1,4,7 are for heavy clay soils; 2,5,8 for light clay; and 3,6,9 for loamy soils. Also shown are cumulative yield probabilities (line 10).

General Conclusions

There appears to be a potential for growing irrigated wheat in many parts of south-east Asia. At low elevations potential yields of 3 - 5 t ha^{-1} may be expected, and about 1.0 t ha^{-1} more for every 400 m increase in elevation (up to 2000 m). Success in unirrigated areas was related to the presence of deep soils and dry season rainfall. Since wheat would be sown towards the end of the rainy season, which, in this region, is heavy, the water content of the soil profile at sowing time would be close to field capacity. Depending on the sowing date and dry season rainfall, 30% to 90% of the yield potential could, therefore, be realized without irrigation.

Acknowledgement

We are grateful to Mr Samuel P. Liboon, Ms Cecilia H. Reyes, and Ms Maridel A. Dizon for their help in conducting these studies. The staff of Agroclimatic data bank of IRRI provided the weather data. Thanks are due to Drs V. R. Carangal, D. P. Garrity and R. K. Pandey for reading the manuscript.

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8. Estimation of optimal duration of wheat crops in rice-wheat cropping systems by crop growth simulation

Abstract

Wheat in Indo-Gangetic plains is generally grown after rice. Optimal duration of wheat in different locations is determined by repeated field experiments. In this paper, we have used crop growth simulation to determine optimal duration of wheat at few representative locations. The optimal duration varied with location and sowing dates. For normal sowings (15 November), the most suitable varieties were early maturing types in areas such as Punjab, medium maturing types in environments of New Delhi and Uttar Pradesh and late maturing types in West Bengal and Bihar. Depending upon year-to-year climatic variability, optimal duration of varieties may vary. It is concluded that simulation of the effect of climatic variability on crop growth, development and yield over a period of several years may be helpful in supplementing field experiments to correctly determine the optimal duration of wheat varieties.

Introduction

A large proportion of wheat in India is grown after rice. In these areas sowing of wheat generally gets delayed due to either late planting of rice or use of long duration rice varieties or long turnaround time. Since this increases the risk of exposure of wheat crop to adverse temperatures during grain-filling, grain yields can be reduced. Most wheat area in Indo-gangetic plains is irrigated. Therefore, genotype × environment (G×E) interaction is caused primarily by the differences among genotypes in their capacity to tolerate/escape adverse temperatures. These differences are generally associated with differences in development rates.

Determination of optimal wheat varieties in rice-wheat system is a priority research item for All India Coordinated Wheat improvement Project. A large number of trials are conducted every year at many locations where rice and wheat varieties of different maturity groups are grown in different combinations to identify suitable varieties. Crop growth simulation technique may provide an alternative method of assessing optimal crop duration when sowings are done at different times. In this chapter, such a crop simulation model is used to determine optimal crop duration of irrigated wheat in few typical rice-wheat areas of India.

Published as: Aggarwal, P.K. 1991. Estimation of optimal duration of wheat crops in rice-wheat cropping systems by crop growth simulation. pp 3-10. In. Simulation and systems analysis for rice production. Penning de Vries, FWT, van Laar, HH and Kropff, MJ (eds.). PUDOC, The Netherlands. p 369.

Materials and Methods

The Model

WTGROWS was the model used (Chapter 2). It simulates daily dry mater production as a function of radiation intensity and maximum and minimum temperatures for conditions where biotic and abiotic stresses do not limit crop growth. The model consists of eight sections: crop development, photosynthesis, respiration, carbohydrate partitioning, photosynthetic area, senescence, grain formation and grain growth. The different components of the model take into consideration the climatic variation experienced by the wheat crop in different agro-ecological regions of India.

Effect of Variety

In this study the response of six early, medium and late maturing varieties has been analysed. The varieties were assumed to vary in their heat units requirement for the phase, seedling emergence to anthesis. For simulating the development of hypothetical 'early' varieties, heat units required to reach anthesis were assumed to be 609 and 709 degree-days; for medium duration varieties, 809 and 909 degree-days and for late maturing varieties 1009 and 1109 degree-days. The photoperiodic response was assumed to remain the same. This procedure allowed us to test the effect of phenology on grain yield at different locations without changing any other physiological character. This approach can be considered analogous to use of isogenic lines for evaluating the impact of a particular character (rate of crop development in the present study) on crop growth and yield.

Rice Wheat areas

Indo-gangetic plains, i.e., areas between 24-32°N and 75-92°E have the major concentration of the rice-wheat cropping system. This area is characterized by alluvial soils and semi-arid. Rice is sown in June-July and wheat is sown in the months of November to January. Figure 8.1 shows a typical weather pattern for a representative rice-wheat area. Both maximum and minimum temperatures decline starting from October, reach a lowest value in January before increasing again in February. Daylength is about 12 h in October, decreases to 11 h in January and by April increases to 13 h. During the entire wheat season, the average rainfall is 50 to 100 mm only. Solar radiation is 16 MJ m^{-2} d^{-1} in January and 24 MJ m^{-2} d^{-1} in March. Most of the wheat in rice-wheat belt is irrigated. For this study, few typical locations, namely, Amritsar (31.38°N, 74.52°E, 234 m asl), New Delhi (28.35°N, 77.12°E, 216 masl), Varanasi (25.27°N, 82.52°E, 85 m asl), Patna (25.37°N, 85.10°E, 53 m asl) and Burdwan (23.14°N, 87.51°E, 32 m asl) were selected to represent major agro-climatic zones within rice-wheat areas. The mean temperatures during January at these locations are 11.5, 14.6, 17.1, 17.9 and 20.2 °C, respectively.

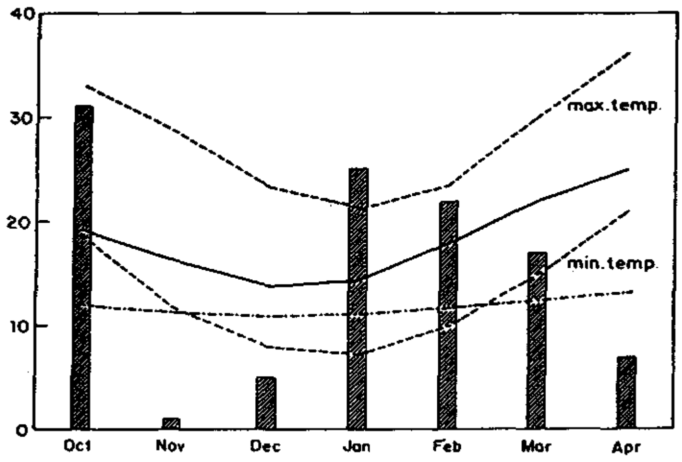

Figure 8.1. A typical weather pattern during wheat growth period in rice-wheat areas.

Results and Discussion

Optimal variety for normal sowing

At most places in the rice-wheat belt, the earliest possible sowing date for wheat is 15 November. This is also considered the optimal sowing date (Bhardwaj et al., 1975). In order to determine the suitable variety for this date of sowing, simulations were carried out for early, medium and late duration varieties for representative locations. The results showed that at Amritsar, the early maturing (709 degree-days to anthesis) variety had a potential yield of 7.91 t ha^{-1} compared to 6.7 t ha^{-1} of Kalyansona (909 degree-days). At New Delhi, the crop with maximum grain yield (7.29 t ha^{-1}) required 809 degree-days (Figure 8.2). The yield of this variety was however only marginally higher than Kalyansona. Thus, medium duration varieties are most suitable in this environment. At Varanasi too medium duration varieties yielded the maximum (6.3 t ha^{-1}). By comparison, in Patna and Burdwan in eastern India, long duration varieties (1009 and 1109 degree-days) were highest yielding (6.05 and 5.19 t ha^{-1}, respectively). Thus it can be concluded that depending upon the weather, choice of variety is determined. Varieties of same phenological class are not suitable for all locations. In Punjab and neighboring areas, short duration varieties are more suitable whereas in Delhi and west Uttar Pradesh medium duration varieties are the highest yielding whereas in Bihar and West Bengal long duration varieties produce the maximum grain.

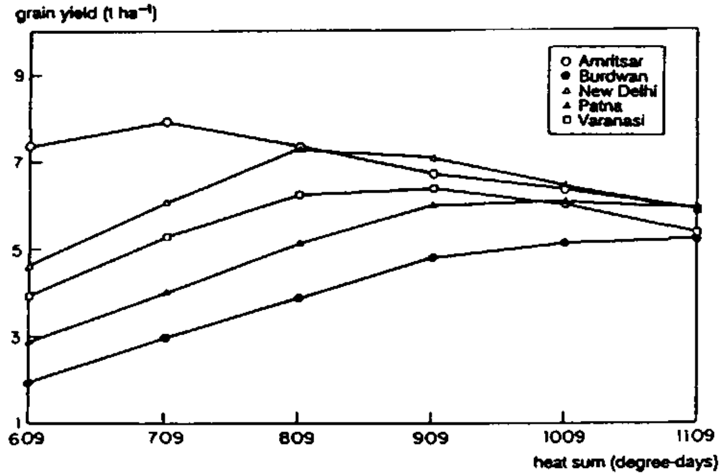

Figure 8.2. Grain yield of early, medium and late maturing varieties of wheat sown on 15 November at different locations.

Effect of late sowing

The effect of late sowing on grain yield was studied for the same locations as above. It was assumed that variety that yielded highest on 15 November is sown at all subsequent dates. The simulations were made for crops sown at 15 November, 1 and 15 December and 1 and 15 January.

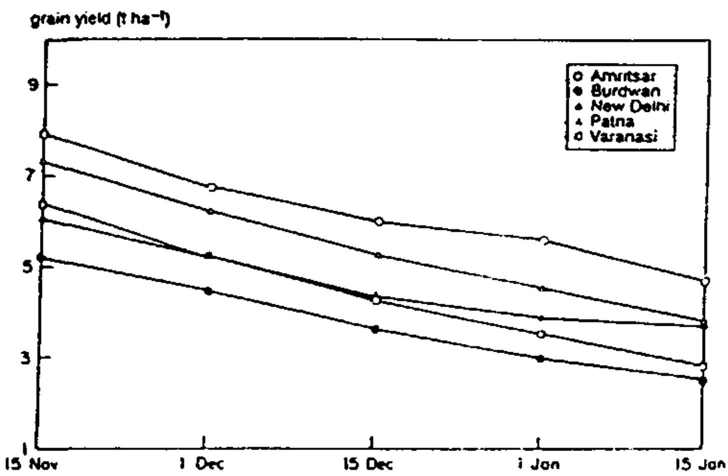

Figure 8.3. Effect of date of sowing on grain yield of wheat at different locations.

Irrespective of the location, delay in sowing decreased grain yield sharply (Figure 8.3). There was almost a linear decrease in grain yield from 15 November onwards. By 15 January the grain yield had decreased to 4.68, 3.80, 2.82, 3.68 and 2.53 t ha^{-1} at Amritsar, New Delhi, Varanasi, Patna and Burdwan, respectively. Assuming a linear decrease from 15 November to 1 January, it can be calculated that late sowing decreased grain yield at a rate of 52.3, 60.0, 61.9, 47.6 and 48.0 kg ha^{-1} d^{-1} delay in sowing at these locations. This is 0.66, 0.82, 0.98, 0.78 and 0.92% of the yield on 15 November.

Optimal crop duration at different sowing dates

Depending upon the date of sowing, the optimal time of flowering and maturity may change with location. The period within which flowering must occur at a site for maximum grain yield, irrespective of the cultivar, is sometimes termed as 'flowering window' (Loss et al., 1990). Wider flowering window suggests considerable time during which anthesis can take place and one can be flexible in selecting the variety. The boundaries of this window were identified by simulating phenology and grain yield of early, medium and late maturity varieties for several sowing dates. The anthesis dates when grain yields were between 95% and 100% of maximum grain yield were taken to represent the boundaries of this window.

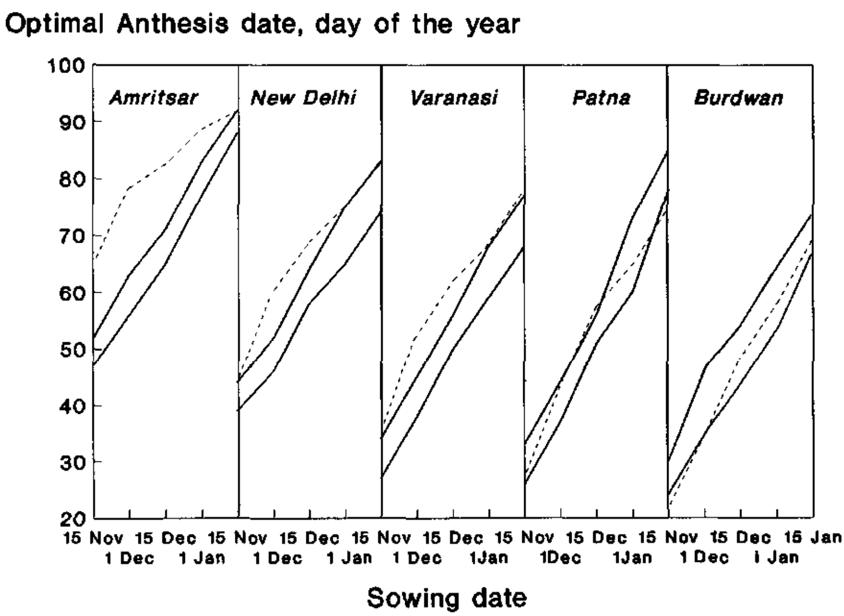

Figure 8.4. Optimal anthesis time of irrigated wheat as a function of sowing time for different locations.

Figure 8.4 depicts this window for different sowing dates. For comparison, the anthesis dates of Kalyansona are also shown. At Amritsar, the desirable flowering duration was always much shorter than that of Kalyansona at all sowing dates. The window was only 5 - 7 days in width irrespective of the sowing time. At New Delhi and Varanasi, for sowing on 15 November, optimal anthesis time was the same as that of Kalyansona but for the sowings done in the month of December, it was much earlier. Therefore, if sowing gets delayed early maturity varieties that are able to build enough LAI may be able to partially compensate some of the sharp losses in grain yield. Indeed, in practice, Sonalika, an early maturing variety is sown in late sowing compared to medium maturity varieties. For January sowings, flowering window was of 9 - 10 days duration. Kalyansona also flowered during the same period. At Patna, irrespective of the sowing date, flowering window was generally 7 days wide. Kalyansona's anthesis date was always within the window. At Burdwàn, the window was of 6 days duration for 15 November sowing and the optimal anthesis time was 6 days later than that of Kalyansona. But for subsequent sowing dates, the mean width of the window was 8 - 9 days and optimal anthesis date was same as that of Kalyansona.

Climatic variability and optimal crop duration

The above analysis is based on long-term mean weather data. Year-to-year variation in weather may affect crop development, growth and yield and thus optimal crop duration may be different. This was studied for New Delhi alone for which daily weather data of last 20 years was available. Simulations were made to assess grain yield of early, medium and late maturing varieties for sowings done on 15 November (normal sowing) and for 15 December (late sowing). The results are presented in Figure 8.5. The curves are cumulative probability distribution functions of simulated grain yield and reflect the ability of different varieties to cope with environmental stresses associated with climatic variability.

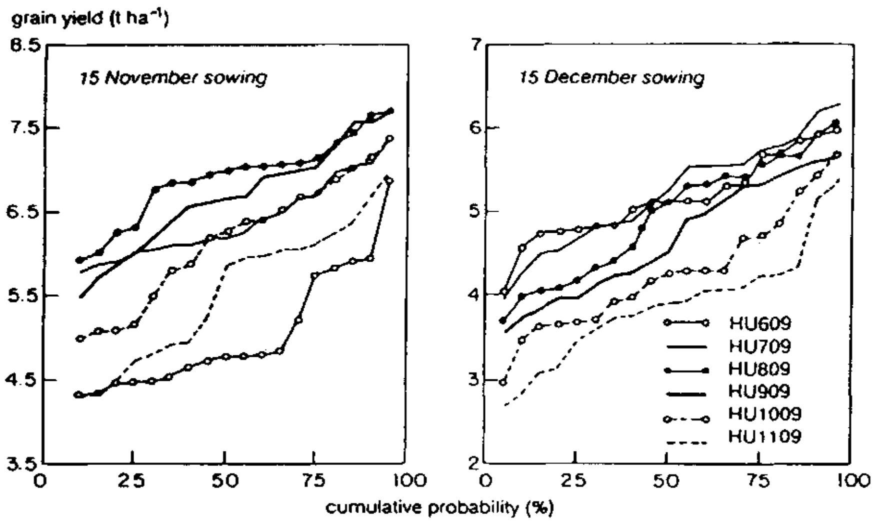

Figure 8.5. Cumulative probability distribution of simulated grain yields of early, medium and late maturing varieties for normal (15 November) and late sowing (15 December).

It was evident that for normal sowing medium duration varieties out-yielded early and late varieties in all years. The grain yield of medium duration varieties ranged between 5.5 and 7.6 t ha^{-1} depending upon the year. At 50% probability level, grain yield of different varieties was 4.8 (609 degree-days), 6.2 (709), 7.0 (809), 6.7 (909), 6.3 (1009) and 5.8 (1109) t ha^{-1}.

This was in close agreement with the results obtained by employing long-term mean weather data (see Figure 8.3).

Comparison between the two medium duration varieties show that in 75% of the years, variety with 809 degree-days requirement out-yielded the one with 909 degree-days requirement, whereas in rest 25% years the yield of both was similar. It implies that in order to correctly determine the optimal duration of wheat, a breeding programme must evaluate lines for a minimum of five years or be supported by growth simulation for a large umber of years to account for the climatic variability.

In late sowings, early maturity varieties were highest yielder followed by medium and late duration varieties. At 50% probability level, grain yield was 5.1 (609 degree-days), 5.24 (709), 5.08 (809), 4.5 (909), 4.24 (1009) and 3.89 (1109) t ha^{-1}, respectively. Strong genotype x environment interaction was again evident. Comparison among two early maturing varieties show that although variety with 709 degree-days requirement surpassed the yield of the variety with 609 degree-days in 75% of the years, in rest of the years it was either equal or less. This again supports our earlier conclusion regarding the length of a breeding programme.

Conclusions

Crop growth simulations show that for different locations, optimal crop duration varies. For normal sowings (15 November), the most suitable varieties are early maturing types in areas such as Punjab, medium maturing types in environments of New Delhi and Uttar Pradesh and late maturing types in West Bengal and Bihar. Grain yields decrease sharply with late sowing; the decrease can be partially offset by selecting variety of optimal duration. Many of these results are also observed in field experiments. Depending upon year-to-year climatic variability, optimal duration of variety may vary. Simulation of the effect of climatic variability on crop growth, development and yield over a period of several years may be helpful in a breeding programme to correctly determine the optimal duration of wheat varieties.

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Loss, S.P., Perry, M.W. and Anderson, W.K. 1990. Flowering times of wheats in South-Western Australia: A modelling approach. Aust. J. Agric. Res. 41: 213-223.

9. Simulating genotypic strategies for increasing rice yield potential in irrigated, tropical environments

Abstract

Irrigated rice yield potential needs to be increased. A simulation model was used to examine the opportunities for doing so in the dry season of a tropical climate by altering durations of juvenile and panicle formation phases, specific leaf area, maximum leaf N concentration, spikelet growth factor and potential grain weight. The study was conducted for three levels of N management: practices followed in breeder's screening plots; agronomic recommendations for high yield potential; and growth-rate-driven N uptake. The results revealed that IR72, the check cultivar, has a large yield potential that can be realized with better N management. No trait individually or in combination provides more than 5% advantage in yield in the level of management typically practiced by breeders. In such environments, even though genotypes may possess traits for higher yield potential, they will not be able to express them. The simulations predict that significantly higher rates of N input and precise timing are required to attain a grain yield potential higher than 10 t ha^{-1}. If plant N status can be increased without lodging or disease problems, a significant increase in yield requires increased sink capacity, maintenance of high leaf N content and a longer grain-filling duration.

Introduction

Irrigated rice yield needs to increase by 60 to 70% by 2025 to meet the food demand of the increasing population (Hossain, 1995). But, rice yield potential has remained constant at about 10 t ha^{-1} in the dry season of tropical environments over the past 30 years (Kropff et al., 1994a), although the newer recent cultivars have earlier maturity and greater per-day productivity. Designing and evaluating new plant types for higher yield potential are, therefore, receiving increased attention (Khush, 1990).

In crop improvement programmes, rice breeders typically select for several morphological features that affect growth, development and yielding ability. Ideotypes, however, should be based on sound understanding of underlying physiological and biochemical processes associated with morphological changes. A working group consisting of physiologists, biochemists, molecular biologists, agronomists, soil scientists, geneticists and breeders short-listed several issues related to increased biomass production and sink capacity that merit further investigation for increasing yield potential (Cassman, 1994). The key traits were: increased specific leaf N and rate of photosynthesis per unit specific leaf N; optimization of

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light interception; strategies for reduced respiratory losses and delayed senescence during grain-filling, independent of sink size; higher crop growth rate during reproductive stages; a reduction of excessive tillering to increase sink size; and a slower rate of individual grain-filling to extend grain-filling duration.

Research experiments for detailed physiological and molecular investigations of such a large number of traits and their interactions would require tremendous resources and time. Moreover, the expression of different plant traits and their impact on yield potential may vary with agronomic management. Crop simulation models can integrate knowledge of physiological processes and morphological traits to help explain yield formation in environments varying in physical, biological and agronomic factors. These simulations and sensitivity analyses can therefore be used to evaluate key interactions quickly and identify those traits with the greatest impact on yield potential. The results can then be used to improve the efficiency of field and greenhouse experiments to test hypothesis about plant types for increased yield potential.

A number of studies have been conducted in recent years where simulation models were used for determining critical traits for higher yield potential in rice (Dingkuhn et al., 1991a; Penning de Vries, 1991; Kropff et al., 1994a; Aggarwal et al., 1996) and many other crops (see reviews by Boote and Tollenaar, 1994; Kropff et al., 1995). These studies concluded that higher yield potential is possible only when source capacity, sink size and grain-filling duration are increased simultaneously. Except for Dingkuhn et al. (1991a), however, the focus of such studies was on environments without growth limitations. Rice in Asia is grown in a wide range of production environments. Many of them are suboptimal in water and nutrient availability. N is a common limiting factor, even in large parts of irrigated rice areas. At the International Rice Research Institute, rice germplasm is screened by breeders in the dry season in field plots that receive total application of 115 kg N ha^{-1} in three splits. In contrast, the agronomic recommendation for higher yield potential is 145 kg N ha^{-1} in four splits. Cassman et al. (1994) developed a conceptual framework on N supply and demand relationships, indicating that high yields necessitate maintaining soil N availability in proportion to the crop growth rate-determined minimum N uptake rate. In this chapter, our objective was to evaluate by crop growth simulation the importance of traits related to crop duration, leaf area, N demand and sink capacity in irrigated, tropical lowland environments varying in timings and quantities of N availability.

Materials and Methods

The approach

The impact of individual traits was assessed by changing the specific crop parameters of a deterministic crop simulation model calibrated for a common tropical rice cultivar IR72 (Kropff et al., 1994b). The impact of simultaneous change in many traits was assessed by the Monte Carlo simulation technique commonly used in quantitative population genetics studies (Crosby, 1973; Aggarwal, 1995, Chapter 3). In this approach, different traits were considered to be stochastic. This technique allows determination of the extent of divergence required from the mean value (IR72 in our study) of different traits and their consequence on yield potential. A total of 500 hypothetical genotypes was 'created'. Each of these had a random combination of values for the different traits that ranged between the specified minimum (20% less than IR72) values and maximum (20% more than IR72) values. Values smaller than IR72 were also used to examine if reduction in some traits might be advantageous to other traits. The random values for different traits were generated using the program RIGAUS (Bouman and Jansen, 1993). It was assumed that the selected values were distributed uniformly over the specified range of values. Every simulated genotype was unique in its trait 'makeup' thus mimicking the random segregation behavior of progeny when two parents are hybridized.

This set of random input values was used in the simulation model to compute corresponding yield values. The generated values for different traits were not correlated among themselves. The relative change in grain yield was calculated as the ratio of the difference between a hypothetical genotype and IR72 relative to the simulated yield of IR72. This relative measure makes it easier to assess the impact independent of the yearly variations.

Climate data for the dry season of Los Baños, Philippines, was used in model simulations to represent a typical tropical environment with high yield potential. The impact of change in individual traits was simulated using 10 years of weather data. A preliminary study indicated that use of more years of weather data did not have much effect on the yield variability of the dry season, irrigated rice (data is not presented). To keep simulations to a manageable limit, impact of simultaneous variation in different traits was studied using only 3 years of contrasting weather data. The growth of IR72 and hypothetical plant types was simulated for the dry season with a transplanting date of 21 January. The uptake of indigenous soil N was set to 0.6 kg N ha^{-1} d^{-1}, which is typical of fields of high fertility at the IRRI farm. The simulations assumed absence of water stress, nutrient limitations other than N, or biotic stresses.

Three N management environments were simulated. The first mimicked germplasm screening plots where 115 kg N ha^{-1} is applied in three splits: 20 kg basal; 45 kg at mid-tillering; and 50 kg at the panicle initiation stage. The second treatment was based on N recommendations for high yield potential in the dry season of the tropics with 30, 45, 50 and 30 kg N ha^{-1} applied at the time of transplanting, mid-tillering, panicle initiation and flowering. The final treatment assumed daily supply equivalent to estimated requirement to maintain maximum N content throughout growth.

Additional simulations were done to determine the impact of different traits when thermal time for grain-filling phase was allowed to increase by 30%, equivalent to an additional 9 to 10 d in tropical environments. Grain growth was terminated earlier in the model, however, if the source was exhausted or the sink filled.

The crop model

The ORYZA_1 model (Kropff et al., 1994b) was the basic model used. It describes crop growth and development as effected by solar radiation and temperature with no other external factor affecting growth. Model input requirements were geographical latitude, daily maximum and minimum temperatures, solar radiation, plant population, and dates of seeding and transplanting. Specification of cultivar characteristics is also required including phenological development rates, relative leaf area growth rate, specific leaf area, spikelet formation factor, potential grain weight, leaf N content and fraction of stem reserves.

Model modifications

The input requirement of leaf N content restricts the use of ORYZA_1 to environments without N stress or to situations where leaf N pattern is known. The model was, therefore, modified to include prediction of N availability and crop uptake in irrigated rice fields, and the allocation and redistribution N within the plant.

In the model, total N uptake by the crop was determined by the interaction of crop N demand, the available soil N supply, and the N uptake efficiency from applied N fertilizer using an approach that follows the earlier models, ORYZA_0 (Ten Berge et al., 1994) and ORYZA_N (Drenth et al., 1994). Daily crop N demand was estimated by the difference between the maximum and actual N content of the plant. Maximum N content was estimated by the N sum of different organs, each a product of the organ dry weight and its maximum N concentration at a given development stage.

The root zone of the soil profile was considered as one single compartment in which all mineral N was potentially available for crop uptake. The N supply included both the indigenous N from the soil-floodwater system and N applied from applied fertilizer. It was assumed that a constant amount of indigenous N was added to the soil N pool everyday. This was estimated by measured rates of N uptake in field plots without applied N (Cassman et al., 1994). Although uptake of applied N is sensitive to management, soil type, and climate, with good management the recovery efficiency typically increases from relatively low values from basal N applications incorporated in the soil at transplanting to much higher recoveries from applications broadcast into floodwater at panicle initiation (De Datta, 1986). In the model, the N fertilizer recovery was specified to increase linearly from 35% from N applied at transplanting to 75% at panicle initiation and thereafter. The observed maximum value of N uptake rate in various soils and genotypes range from 3 to 8 kg N ha^{-1} d^{-1} (Ten Berge et al., 1994). Because the dependence of this variable on crop development stage, roots and environmental conditions is not fully understood, we assumed a maximum value of 8 kg N ha^{-1} d^{-1}. Total available soil N was thus the measured N uptake from field plots without applied N plus the amount of N fertilizer multiplied by the recovery fraction. This pool was depleted daily depending on the crop N uptake.

Nitrogen acquired by the crop was allocated to different plant organs in proportion to their relative sink strength as determined by partitioning factors sensitive to stages of development and N supply. Root-shoot ratio increased if crops experience N stress, which was defined as the ratio of actual and potential N content. Grain N demand was met by mobilization from vegetative organs, and N concentration of the developing grains was held between a minimum and a maximum value. The minimum N value was determined by the total crop N content at anthesis stage (Drenth et al., 1994) while the maximum was set at 1.75% N. The N loss from the crop was restricted to the residual N content of senescent plant parts. The net N content of leaves and stems was the sum of their daily allocation, N uptake, N translocated to grains and N lost to senescence. Leaf and stem N in excess of the residual N content was assumed to be available for translocation to grains although the actual N translocated on a given day would not exceed 10% of the amount available.

Shading in very dense canopies accelerates senescence. Senescence in the modified model increased when leaf area index exceeded 4 m^2 m^{-2} following the approach used by Van Keulen and Seligman (1987).

Evaluation of the crop model

The basic models - ORYZA_1, ORYZA_0 and ORYZA_N have been validated in several experiments that included N fertilizer treatments, different cultivars, seasons and locations in Asia (Ten Berge et al., 1994; Drenth et al., 1994; Kropff et al., 1994a). The models predicted biomass and grain yields reasonably well over a range of 2 to 15 t ha^{-1}. Two replicated field experiments conducted at IRRI experimental farm in Los Baños (14°N), Philippines, in the dry seasons (DS) of 1992 and 1993 were used for validating the performance of the modified model. The 1992 experiment used IR72 and included treatments of 0, 180 and 225 kg N ha^{-1}. More details of this experiment were given by Kropff et al. (1994b). The second experiment also used IR72 and consisted of 17 treatments with N fertilizer rates ranging from 0 to 400 kg N ha^{-1} with different split timings (Wopereis et al., 1994).

The traits simulated

The impacts of increased crop duration, source and sink capacity were assessed by altering the crop parameters associated with them. The effect of a 20% decrease in the rate of either juvenile period (average increase in crop duration, 10 d) or panicle-formation period (average increase in duration, 5 d) was examined, although greater variability is known (Vergara et al., 1969), because existing cropping systems may not allow large increases in crop duration. The impact of increased LAI was simulated by increasing specific leaf area by 20% relative to IR 72 based on the maximum variability among rice cultivars, as reported by Sutoro and Makarim (1995). To simulate the effect of increased crop N demand, the maximum leaf N concentration (which changes with crop development) of IR72 was increased by 20% for all development stages although variability in this trait is not well established. Sink capacity in the model depended on the number of spikelets and potential kernel weight. The number of spikelets per unit ground area was determined by the cumulative crop growth between panicle initiation and flowering. Grains accumulated dry matter if available and until potential grain weight (input in the model) was reached, or until physiological maturity which depends on thermal time. The impact of increased sink size was assessed by increasing the slope of the relationship between spikelet number and crop growth (spikelet formation factor) or by increasing potential grain weight. Large variation has been documented among rice cultivars for both factors (Kropff et al., 1994a; Sutoro and Makarim, 1995). In the present study, the default values of IR72 (64.9 spikelets per kg dry matter and 25 mg per grain at 14% moisture) were increased by 20%, respectively, to study the impact of increased sink capacity.

Results and Discussion

Model evaluation

In general, the model estimated patterns of LAI accurately for all N fertilizer treatments in the 1992 experiment, although there was a slight underestimation during the early growth stages (Figure 9.1). Total N uptake was also simulated accurately for 0- and 180-N treatments, but N uptake after flowering was overestimated for the 225-N treatment. The model underestimated dry matter accumulation for all three treatments, particularly during initial stages. Perhaps this was due to inadequate description of N effects on early growth of leaf area. Moreover, the soil N supply model used in this analysis with a standard rate of 0.6 kg N ha^{-1} d^{-1}, and a maximum N uptake rate of 8 kg N ha^{-1} d^{-1}, irrespective of N application rate, may not accurately reflect the actual pattern of N supply and uptake in that field.

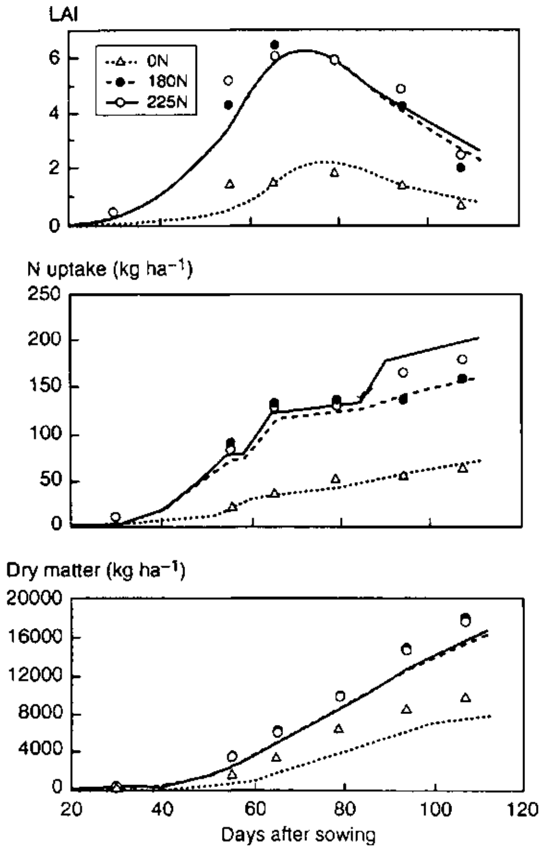

Figure 9.1. Comparison of temporal changes in simulated and observed leaf area index, total N uptake and dry matter of IR72 grown at 0, 180 and 225 kg N ha^{-1}.

Simulated grain yields and dry matter at maturity were compared with measured values of the 1993 experiment. Measured and simulated grain yields varied between 4.4 t ha^{-1} and 10.1 t

ha^{-1} (Figure 9.2). Mean actual and simulated grain yields were 8.0 and 8.1 t ha^{-1}, respectively. Actual and simulated total dry matter had a similar relative magnitude of variation. Mean measured and simulated dry matter were 17.3 and 17.6 t ha^{-1}, respectively, indicating good agreement between the two. For most treatments, simulated and measured values were in close agreement except for treatments in which no N fertilizer was applied before flowering and 150 to 300 kg N ha^{-1} was applied at/or after flowering. It is likely in these treatments that massive application of N to a N-deficient crop resulted in a very high rate of N uptake, increasing the growth rate more than was simulated. In the model, the maximum N uptake rate was not allowed to exceed 8 kg N ha^{-1} d^{-1}.

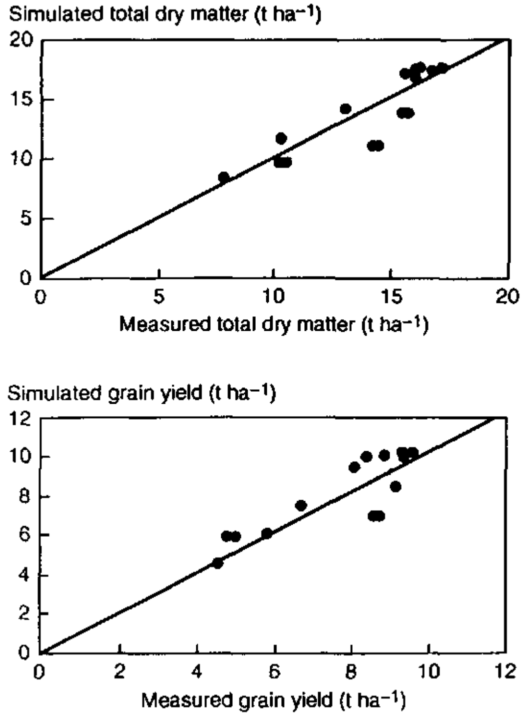

Figure 9.2. Comparison of simulated and measured dry matter and grain yield at maturity of IR72. Each point is a treatment varying in quantity (0 to 400 kg N ha^{-1}) and/or schedule (1 to 7 splits) of N application.

Simulated impact of individual traits

Current N management in breeder's plots

Without changing plant traits and with only 115 kg N ha^{-1} applied following practices in breeder's plots, IR72 took 64 d to panicle initiation, another 25 d to anthesis, and 31 d for grain-filling. The crop followed a typical pattern of LAI development with a maximum LAI of 6. Specific leaf N was 2 g N m^{-2} at the seedling stage but declined to 1.25 g N m^{-2} leaf area by anthesis and to 0.5 as the crop approached maturity. Dry matter production was 14.9 t ha^{-1} and mean grain yield was 7.7 t ha^{-1}. The crop was not sink-limited because actual grain weight was less than the potential grain weight. Grain growth was, however, terminated due to achievement of physiological maturity dictated by thermal time, although green LAI was still 2.0 at that time. When the maturity restriction was removed, grain growth continued for another 10 d but in this additional period dry matter accumulation was only 0.6 t ha^{-1} because of rapid senescence and low specific leaf N (Table 9.1).

Table 9.1. Simulated impact of alteration in different plant traits on rice grown under current N management practices in the breeders plots in the dry season at Los Baños, and with and without an increase in grain-filling duration.

Altered plant trait	Thermal time for GFD[a]							
	Standard				30% increase			
	GYb	GNO[c]	GW[d]	TDM[e]	GY[b]	GW[d]	TDM[e]	GFD[a]
Control (IR72)	7.7	37500	20.5	5.5	8.4	22.3	6.1	41
Juvenile phase	7.9	38200	20.8	5.6	8.5	22.4	6.2	40
Panicle formation stage	7.9	46800	16.8	5.4	8.4	18.1	5.8	40
Leaf N concentration	7.7	37400	20.7	5.6	8.4	22.6	6.2	41
Specific leaf area	7.7	38800	19.8	5.5	8.3	21.3	5.9	41
Spikelet growth factor	7.7	45000	17.1	5.5	8.4	18.6	6.1	41
Potential grain weight	7.7	37500	20.5	5.5	8.4	22.3	6.1	41

[a] GFD grain-filling duration (d), mean GFD was 30-31 d with standard thermal time.

[b] GY weight of rough rice at 14% moisture (t ha^{-1}).

[c] GNO grain number m^{-2}.

[d] GW individual grain weight (mg).

[e] TDM above-ground dry matter during grain-filling (t ha^{-1}).

Reducing the rate of development of the juvenile phase increased the duration of the vegetative phase by 8 d. Total dry matter at anthesis was 1 t ha^{-1} more than that of IR72 but this did not translate into an increase in grain yield due to attainment of thermal time limit for grain-filling. Removal of that restriction did not increase grain yield, however, due to low specific leaf N content during the extended period and maintenance respiration associated with the increased dry matter accumulated before flowering. Reducing the rate of development during panicle formation stage increased the duration of this phase by 6 d. Consequently, dry matter and grain number increased (Table 9.1), but there was no significant increase in grain yield with or without extension of grain-filling duration.

Increase in specific leaf area or maximum leaf N concentration also had no effect on dry matter production and grain yield (Table 9.1). The increase in specific leaf area resulted in greater leaf area index and light interception but due to an associated decrease in specific leaf N, there was no effect on growth rate. Increase in LAI during early canopy development would have effected growth rate but, in the model, early leaf area development is independent of specifie leaf area. Increased maximum leaf N concentration created an additional crop demand for N, which resulted in faster uptake of available N and consequently an increased specific leaf N and gross photosynthesis rate up to panicle initiation. Thereafter, the crop was N deficient, which caused faster leaf senescence and no increase in yield.

Increasing sink capacity by either increasing the number of spikelets or by increasing the potential grain weight also had no effect on grain yield (Table 9.1). In both cases, crop growth was terminated due to attainment of physiological maturity. When this limitation was removed, grain-filling duration increased by 9 d but the increased sink capacity was not filled due to lack of increased post-anthesis dry matter accumulation (Table 9.1). Thus, relative to IR72, increased sink capacity had no effect on grain yield.

Recommended N management for high yield potential

In this treatment, an additional 30 kg N ha^{-1} was applied at flowering. This increased IR72's specific leaf N during panicle formation and grain-filling stage by 15 to 20% and delayed the senescence rate. The increased growth resulted in relatively more maintenance respiration but the increase in gross photosynthesis was sufficient to achieve greater dry matter, individual grain weight and yield (Table 9.2). Grain yield in this treatment was 1.1 t ha^{-1} more than with the N management used in breeder's plots. This increase is comparable with the increase from N application at flowering in field conditions reported by Kropff et al. (1993). Our simulation results also reveal that by maturity, the grains had attained 94% of their potential weight and, therefore, when the thermal time restrictions were lifted, there was an increase of only 5 d in grain-filling duration and 0.1 to 0.2 t ha^{-1} in dry matter and grain yield (Table 9.2).

Table 9.2. Simulated impact of alteration in different plant traits on rice grown under recommended N management practices for high yield potential in the dry season at Los Baños, and with and without an increase in grain-filling duration.

Altered plant trait	Thermal time for GFD[a]							
	Standard				30% increase			
	GYb	GNO[c]	GW[d]	TDM[e]	GY[b]	GW[d]	TDM[e]	GFD[a]
Control (IR72)	8.8	37900	23.2	6.5	9.6	25.0	7.1	37
Juvenile phase	9.0	38600	23.4	6.6	9.7	25.0	7.2	36
Panicle formation stage	9.0	47300	19.1	6.4	10.1	21.3	7.2	40
Leaf N concentration	8.8	37900	23.4	6.5	9.5	25.0	7.1	36
Specific leaf area	8.9	39400	22.6	6.5	9.8	24.8	7.3	39
Spikelet growth factor	8.8	45500	19.4	6.5	10.0	21.9	7.5	41
Potential grain weight	8.8	37900	23.2	6.5	10.0	26.3	7.5	41

[a] GFD grain-filling duration (d), mean GFD was 30-31 d with standard thermal time.

[b] GY weight of rough rice at 14% moisture (t ha^{-1}).

[c] GNO grain number m^{-2}.

[d] GW individual grain weight (mg).

[e] TDM above-ground dry matter during grain-filling (t ha^{-1}).

Increases in duration of the juvenile phase, specific leaf area and maximum leaf N content had little effect on grain yield with or without increase in grain-filling duration because post-anthesis dry matter did not increase due to N deficiency in the canopy (Table 9.2). Increasing the sink capacity by either increasing the number of spikelets or by increasing potential grain weight or by increasing the duration of panicle formation had no significant effect on grain yield unless the grain-filling duration was extended (Table 9.2).

Growth-rate-driven N management

IR72 in this treatment always maintained relatively higher specific leaf N particularly during the crucial stages of panicle development and grain-filling. Relative to the other treatments, which lacked late applications of N, the crop had greater dry matter production in both vegetative and grain-filling stages and a mean grain yield of 9.6 t ha^{-1}. This yield level is comparable with the yield achieved in the field studies of Cassman et al. (1993) and Kropff et al. (1994a) with N rates of 225 kg N ha^{-1}, which included an application of 45 kg N ha^{-1} during flowering. The crop maintained more LAI throughout the grain-filling period than in the recommended management treatments of Table 9.2. Grain number was also larger and yet the grains attained 98% of their maximum weight, indicating a sink limitation. Removal of the thermal time restriction therefore had only a small effect.

Table 9.3. Simulated impact of alteration in different plant traits on rice grown under crop demand-driven N management practices in the dry season at Los Baños, and with and without an increase in grain-filling duration.

Altered plant trait	Thermal time for GFD[a]							
	Standard				30% increase			
	GYb	GNO[c]	GW[d]	TDM[e]	GY[b]	GW[d]	TDM[e]	GFD[a]
Control (IR72)	9.6	39200	24.6	7.2	9.9	25.0	7.4	32
Juvenile phase	10.1	40700	24.9	7.4	10.3	25.0	7.6	31
Panicle formation stage	10.1	48800	20.8	7.3	11.9	24.4	8.8	40
Leaf N concentration	9.9	40000	24.8	7.4	10.1	25.0	7.6	31
Specific leaf area	10.0	40700	24.5	7.4	10.3	25.0	7.7	33
Spikelet growth factor	9.7	47000	20.8	7.3	11.5	24.5	8.8	40
Potential grain weight	9.7	39200	24.9	7.3	11.4	29.2	8.7	40

[a] GFD grain-filling duration (d), mean GFD was 30-31 d with standard thermal time.

[b] GY weight of rough rice at 14% moisture (t ha^{-1}).

[c] GNO grain number m^{-2}.

[d] GW individual grain weight (mg).

[e] TDM above-ground dry matter during grain-filling (t ha^{-1}).

Increase in crop duration resulted in greater total dry weight but almost negligible change in dry matter accumulation during grain-filling. The grains reached potential grain weight before the thermal time limit. In contrast, increased duration of the panicle formation phase gave greater total growth in that critical period and greater grain number. Grains could not achieve potential weight due to thermal time restrictions. Without this limitation, grain-filling duration and yield increased (Table 9.3). The responses to increase in specific leaf N and specific leaf area were similar to those in treatments with the recommended N management.

Increasing sink capacity by either increasing the number of spikelets or by increasing potential grain weight did not change grain yield (Table 9.4). When the thermal time restriction was removed, the grain-filling duration was extended by 9 d and yields reached 11.5 t ha^{-1}, a 16% increase over IR72.

Table 9.4. Traits of selected varieties yielding 12 t ha^{-1} or more at growth rate-driven N management and with extended grain-filling duration.

Variety	% change in			Pot. GW[1]	PFP	GNO	GW
	Nmax	SLA	SPGF				
Control (IR72)	0	0	0	22.0	25	40000	22.0
Group 1							
31	2	1	13	27.9	24	43500	24.6
59	3	2	−1	26.9	29	45700	23.1
87	15	0	17	28.0	24	45100	24.1
92	8	12	7	25.9	27	47600	22.9
126	0	13	−3	28.5	29	45200	23.3
180	17	−6	4	28.5	23	38100	27.9
313	15	5	12	29.1	26	47900	22.9
343	7	13	15	30	25	48100	22.5
375	19	-16	2	28.8	29	46200	23.0
396	14	17	17	26.4	29	53700	20.0
419	1	7	17	27.3	30	55100	19.1
444	17	0	16	26.3	25	46600	23.3
488	4	20	17	24.1	25	49000	22.3
Group 2							
55	2	2	17	24.4	28	52600	20.1
100	−3	15	14	21.9	26	49300	21.6
167	12	2	14	23.7	28	52300	20.9
195	11	14	−11	29.9	30	45100	24.8
198	17	−18	0	26.9	26	41700	25.7
215	−2	12	−17	29.0	26	37000	28.7
258	−9	1	12	27.0	23	43300	24.6
286	−11	12	7	21.9	28	50300	21.2
304	16	17	−6	29.4	23	37600	29.3
308	1	0	5	27.0	26	44900	24.2
362	5	−18	10	27.4	26	45600	23.3
366	3	−11	16	27.4	28	52500	20.6
435	−3	0	14	26.0	28	52000	20.5

[1] (Potential)GW: individual grain weight (mg); PFP: duration of panicle formation phase (d), GNO: grain number m^{-2}; Nmax: maximum leaf N concentration (%); SLA: specific leaf area (m^2 g^{-1}); SPGF: spikelet growth factor (number kg^{-1} dry matter).

Simulated impact of combination of traits

Current N management in breeder's plots

Of 500 hypothetical genotypes, 221 yielded more than IR72, but the maximum increase was only 4.4%. All others had either the same or lower yield than IR72. Because this increase is not more than the impact of individual traits (Table 9.1), data for this analysis are not presented. There was a strong negative relation between final grain number and grain weight although both spikelet growth factor and potential grain weight were increased simultaneously in several genotypes. This was due to limited post-anthesis dry matter divided among a large number of grains. In the field, however, staggered grain-filling within the panicle and spikelet abortion may help in maintaining a constant grain weight.

Several genotypes had increased specific leaf area and N concentration but these did not produce more dry matter. Table 9.1 reveals that increasing vegetative crop duration or sink capacity alone cannot provide an advantage in yield. When combined, the two traits did not have any additive effect on yield because grain growth was terminated by the thermal time limit. We conclude that different combinations of these traits will not increase yield at the relatively low N supply of this treatment, and thus it will be hard to select cultivars with a significant increase in grain yield potential at the current level of N management practiced in breeder's screening plots.

When thermal time restrictions were removed to allow grain-filling to continue, grain yield of IR72, with current N management and no change in any trait, increased from 7.8 to 8.3 t ha^{-1} (Figure 9.3A). Several simulated genotypes (185) had higher grain yield but the maximum increase was only 4%. Larger increases were not possible due to reduced growth rates in the extended grain-filling period, due to increased maintenance respiration and dilution of leaf N.

Recommended N management for high yield potential

A total of 177 genotypes yielded more than IR72 but the maximum increase was only 4%. This was only marginally better than the effect of individual traits. When grain-filling duration was increased, grain yield of IR72 increased to 9.6 t ha^{-1}. Simulated genotypes were, at best, only 6.5% better than IR72 (Figure 9.2). All higher-yielding genotypes had increased sink capacity caused by different combinations of increased duration of the panicle formation phase, spikelet-growth factor or potential grain weight. Their response was similar to that observed by changing the individual factors regulating sink capacity (Table 9.2). The results also revealed that at this level of N management, there is no necessity to increase crop growth rate by increasing either leaf area index or specific leaf N (data not shown). Furthermore, reducing either of them would not have any negative effect as is evident by the performance of several hypothetical genotypes where both specific leaf area and N concentration were less than those of IR72.

Growth-rate-driven N management

With growth-rate-driven N management, IR72 yielded 10.0 t ha^{-1}, which is 23% more than its yield with current management in germplasm screening plots (Table 9.1). Without an increase in grain-filling duration, a total of 246 genotypes yielded more than IR72; the maximum yield achieved was 11.2 t ha^{-1}. Six genotypes yielded at least 10% more than IR72. A major cause of increased grain yield of these lines was a 9 to 14 d increase in the growth duration.

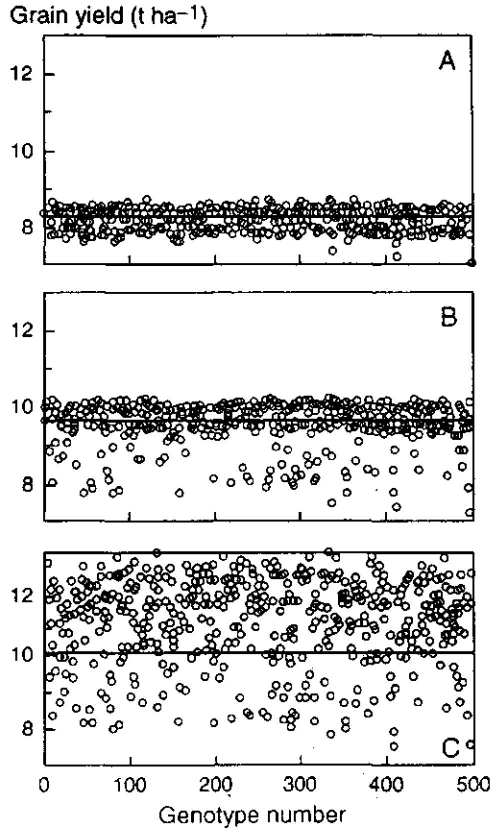

Figure 9.3. Simulated grain yield of 500 hypothetical genotypes characterized by different combinations of traits grown with (A) current N management practices, (B) recommended N management and (C) growth-rate-driven N supply. Each point represents a genotype. The horizontal line in each figure is the yield level of check cultivar IR72 in that management.

When the thermal time for grain-filling was increased, grain yield of IR72 increased only by 0.2 t ha^{-1} because the crop attained its potential grain weight and thus had a sink limitation. When this constraint was removed by increasing sink capacity either by increased spikelet growth factor or potential grain weight, however, grain-filling duration increased by 9 to 10 d, substantially increasing post-anthesis dry matter accumulation and grain yield for several genotypes (Figure 9.3). There were 135 genotypes that yielded more than 12 t ha^{-1}. All of these had greater sink capacity established either by increased spikelet-growth factor, or potential grain weight, or greater duration of the panicle formation stage. In addition, dry matter during grain-filling was increased by 1.3 to 2.2 t ha^{-1}. Table 9.4 lists characteristics of some selected high-yielding genotypes classified by duration. Group 1 consisted of genotypes with a small change in duration. Relative to IR72, these lines had higher specific leaf area, or higher maximum leaf N concentration, or both, resulting in increased dry matter particularly during grain-filling, except for genotypes 31 and 59, which had almost no change in either of these traits. Thus, increased sink capacity and longer grain-filling duration were the main causes of increased grain yield. There was only a marginal increase in the total dry matter at anthesis.

Group 2 consisted of genotypes with 2 to 8 d increase in crop duration. These lines had 1.0 to 2.0 and 1.2 to 2.0 t ha^{-1} increase in dry matter accumulation before and after anthesis, respectively. Although most genotypes in these groups had larger specific leaf area or maximum leaf N concentration than IR72, there were some with 10 to 20% less specific leaf area than IR72 (for example, nos. 118, 198, 362 and 366). It was not always necessary to have a large compensatory increase in maximum leaf N concentration in such genotypes (as in nos. 362 and 366). Genotypes 100, 258, 286 and 435 had lower maximum leaf N concentration than IR72. In such cases, there was no corresponding increase in specific leaf area.

Conclusions

Sensitivity analysis of crop inputs of simulation models has often been used to determine plant traits critical for greater yield potential. In this chapter, we have presented a conceptual approach to simulating stochastic mutations as in a typical breeding plot. We have also used this methodology to mimic the consequence of agronomic management practices on germplasm selection. This approach is likely to overcome limitations of using deterministic simulation models in developing concepts for crop ideotypes. The success of this approach depends, however, upon the capability of the simulation model to accurately simulate the mode of action of traits, upon identification of natural variability in traits, and upon genetic linkages among various traits. Incomplete understanding of the physiological processes and databases on natural variability are inherent limitations of the simulation approach. Nevertheless, once these limitations are overcome, the approach can provide useful information on traits required for greater yield potential and on management practices required for their complete expression.

The following are the specific conclusions of this study:

1. The presently available germplasm, similar to IR72, has yield potential of 9 to 10 t ha^{-1} in irrigated, tropical, dry season environments under suitable N management.
2. The growth rate required for greater yield potential can generally be met through better management. Change in plant architecture may be required only when total crop N

demand is met. In such a scenario, increasing the duration of panicle formation phase by a few days would increase N uptake, and sink capacity, and hence yield.

3. Increasing crop duration may increase biomass, but not grain yield, in crops grown at suboptimal N supply. This was also observed in field experiments (for example, Dingkuhn et al., 1991b). Even with abundant N supply, increased crop duration may result in increased yield only if that increase occurs in the panicle formation phase.
4. Sink capacity can be increased by either increasing the length of the panicle formation phase, or by increasing the spikelet growth factor, or by larger potential grain weight. Natural variability in all three of these traits is well-known. Sink capacity has been increased in IRRI's new plant type (Khush, 1990; Peng et al., 1994). But to fill this increased capacity with carbohydrates, it will be necessary to optimize N management (to keep leaf N content reasonably high during grain-filling) and simultaneously increase grain-filling duration. Strong variation in rice grain-filling duration has not yet been found (Yoshida, 1981; Dionora and Kropff, 1995) although it has been documented in some other crops (Boote and Tollenaar, 1994).

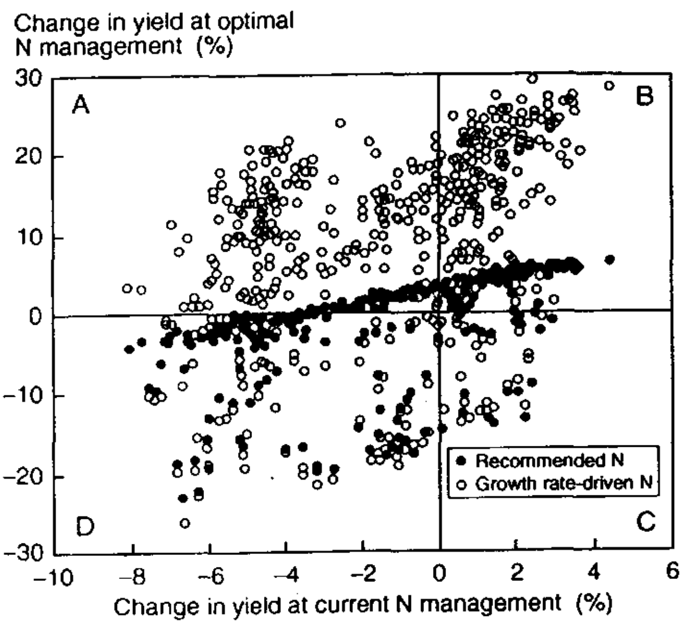

Figure 9.4. Percent change in simulated grain yield of different genotypes (relative to the yield of IR72 at the same management level) grown with practices followed in breeders' germplasm screening plots (current management) plotted against percent change of same genotypes grown with recommended and growth-rate-driven N management. Each point represents a genotype.

5. At the level of N management currently practiced by IRRI breeders, the search for higher yield potential may be impossible even though the germplasm being screened may possess

appropriate traits. These traits need better N supply to express their potential. This is illustrated in Figure 9.4 where the relative change in simulated grain yield of hypothetical genotypes (analogous to breeding lines in a screening plot) grown under current management is plotted against relative change in yield in an environment where crop N demand is met moderately well. All genotypes in quadrant A have substantially greater yield potential than IR72 but would never be selected because they would yield less than the check cultivar under current N-management practices. Genotypes in quadrant B are high-yielding at both levels of management but it would be difficult to identify them with current management due to a relatively small increase in grain yield (<5%) in that environment. Genotypes in quadrant C would yield more with current management but less with improved management. Genotypes in quadrant D would perform poorly in all environments and would invariably be discarded.

6. Simulation analysis indicated that the interactions between source availability, sink capacity and thermal time-determined physiological maturity are very critical and merit greater research attention.
7. Lodging and pest and disease incidence increase in tropical environments when N supply is increased. Current recommendations for N application have been adopted to minimize these constraints, and optimize yield and yield stability. There is a need to examine the 'trade-off trap' between yield loss and variability due to pests and lodging and the increased yield potential due to higher N application to determine if greater yield potential is possible in field environments.

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10. Using simulation models to design new plant types and to analyse genotype by environment interactions in rice

Abstract

Crop simulation models may be able to assist in plant breeding improvement programmes through the identification and evaluation of critical traits needed to develop new plant types for different regions and for management systems. In addition, models may facilitate the use of quantitative understanding of physiology to interpret genotype by environment interactions. The crop simulation model ORYZA1 was used to identify useful physiological traits of a plant type with increased yield potential. The results demonstrated that the relative importance of different traits may change with season and a 20% change in any one individual traits could only provide a small increase in yield potential. For a quantum gain in rice yield potential, it is important that leaf area, leaf N, spikelet number, potential grain weight and grain filling duration are increased simultaneously. With such changes, grain yields higher than 10 t ha^{-1} could be simulated consistently over 32 years in the dry season in Philippines. Various plant types with combination of changes in these traits were simulated to increase yield potential by 15 - 40% over existing plant types. Once a genotype is characterized in terms of its critical physiological traits, crop models may be able to predict its performance in target environments. Examples are presented to demonstrate that crop simulation models are able to produce GxE interactions similar to those observed in experimental data. A framework is described for using crop simulation models and statistical analysis together to increase the efficiency of multi-environment genotype testing. Experiments are now in progress in collaboration with regional, national and international germplasm evaluation networks to explore these opportunities further.

Introduction

The yield potential of current rice varieties in the dry season of tropical environments such as those in the Philippines is about 10 t ha^{-1}. This has not changed significantly since the introduction of IR8 30 years ago (Kropff et al., 1994a). Major achievements have been made by shortening the growth duration from 130 days (IR8) to less than 110 days, along with incorporation of resistance against pests and diseases. At many places in Asia, actual production of rice will be reaching its yield potential in coming decades (Penning de Vries, 1993). Therefore, it is necessary to increase our efforts to raise the yield potential of rice in the tropics.

Breeders spend considerable time and effort in conceptualizing plant types (Hunt, 1993). The largest challenge in ideotype breeding is deciding which traits to combine. Considering the climatic variability where tropical rice is grown and the diverse level of management practices in different regions, different plant types may be needed for the different agro-

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ecological zones. Conceptual physiological models of plant types for increased yield potential have been proposed, but progress has been limited due to the difficulty of identifying critical traits, feedback among physiological processes, evaluation of these traits in specific environments, and lack of genetic variability (Marshall, 1991). Simulation models may prove useful for examining hypotheses and setting breeding goals for different traits by examining historical weather data and applying techniques of risk analysis. Sensitivity analysis of the model parameters is analogous to the creation of genetic isolines since only one parameter is changed while keeping the rest of the plant characteristics constant. They have been used for designing plant types in rice (Dingkuhn et al., 1991; Penning de Vries, 1991; Kropff et al., 1994a) and in other crops (Jordan et al., 1983; Hammer and Vanderlip, 1989; Aggarwal, 1991; Muchow and Carberry, 1993).

Apart from conceptualizing plant types and selecting appropriate parents, line evaluation and release is another major activity consuming considerable resources of plant breeders (Hunt, 1993). Adaptation of newly developed genotypes to different environments is evaluated over several seasons. Simulation models can be used to assist in evaluating and extrapolating the performance of a genotype from one site to another (Dua et al., 1990; Palanisamy et al., 1993). Agroclimatic analysis provides valuable information to breeders about occurrence, severity and frequency of major environmental stresses. Choice of sites for multi-environment testing is often based on such considerations. Crop models can be used to relate environmental variability to plant growth and productivity at different locations and over different seasons and thus help in biological characterization of physical environments. The objectives of this chapter are to examine opportunities for using crop models : a) in identifying critical traits that would result in increased rice yield potential in irrigated, tropical environments and b) in multi-location evaluation of rice genotypes and in interpretation of genotype-by-environment interactions.

Design of Plant Type for Increased Yield Potential

The model ORYZA1 (Kropff et al., 1994b) was used in this study. Under favourable growth conditions solar radiation and temperature are the main factors determining the growth rate of the crop. In the model, the maximum rate of CO_2 assimilation at high solar radiation levels depends upon the leaf N concentration. The total daily rate of CO_2 assimilation is obtained by integrating the instantaneous rates of CO_2 assimilation over the canopy leaf area and over the day. Phenological development rate is a function of ambient mean daily air temperature and photoperiod. Transplanting shock delays crop development and increase in leaf area. Before canopy closure, leaf area development is calculated as a function of mean daily temperature. When the canopy closes, the increase in leaf area is obtained from the increase in weight of leaves multiplied by specific leaf area. Partitioning of dry matter to leaves, stems, and grain is based on a partitioning coefficient that depends on the stage of phenological development. The number of spikelets per unit area is determined by the crop growth rate between panicle initiation and flowering. Adverse temperature at time of meiosis/pollination may result in spikelet sterility. Grains accumulate carbohydrates if available and until potential grain weight (input in the model) is reached or when the crop reaches physiological maturity.

Input requirements of the model are: latitude, daily maximum and minimum temperatures, solar radiation, and dates of seeding and transplanting. Varietal characterization is required in the form of phenological development rates, relative leaf area growth rate, specific leaf area, spikelet formation factor, 1000 grain weight, leaf N content and fraction of stem reserves.

The model has been evaluated from several experiments varying in N input, genotype, time and season of planting (Kropff et al., 1994b). The model predicted potential yields ranging from 6 to 15 t ha^{-1} in a range of contrasting environments reasonably accurately.

Importance of individual traits

The importance of various traits was determined for the dry season and the wet season environments using ORYZA1. Crop parameters for IR72 (Kropff et al., 1994b) and weather data of Los Baños, Philippines for last 32 years were used. The critical model inputs of IR72 were varied by 20% to simulate the effect of an increase in leaf area development, sink size, leaf N content, fraction of stem reserves, shoot:root ratio, leaf:stem ratio, and reduction in maintenance respiration of leaves and crop development rates (increased duration) during juvenile phase and grain filling period. It was assumed that a 20% change in model input will represent extremes of variation available in most plant parameters. Recent data collected at IRRI on rice varietal differences in model inputs suggests that the variation in most of these traits may be close to 20% (Aggarwal et al., unpublished).

Grain yield of the standard crop (IR72) varied between 5.2 and 8.5 t ha^{-1} in the wet season and between 7.6 and 10.5 t ha^{-1} in the dry season. Fifty percent of yields exceeded 6.8 t ha^{-1} in the wet season and 9.0 t ha^{-1} in the dry season. Simulated yields were higher than generally observed experimental yields for the wet season. This was partly be due to higher leaf N content used in the present analysis. Simulated grain yields for the dry season were similar to those obtained in well managed experiments.

The results of varying traits by 20% showed that the crop response varied with the season. Table 10.1 presents summary results of minimum, maximum and median level of changes in the wet season and the dry season. A 20% reduction in the rate of development during basic vegetative period (consequently increase in crop duration to anthesis) decreased yields in some years and increase in some others. Increased crop duration to anthesis often resulted in reduced grain filling duration, increased spikelet sterility and sink limitation depending upon the weather, which resulted in lower grain yields in some years. Increased duration nevertheless resulted in higher LAI and growth. There was a 50% probability that the grain yields would increase by 5% in both seasons (Table 10.1).

Reduction in crop development rate during grain filling allows longer grain filling duration provided there is sufficient sink capacity and source availability. A 20% reduction in development rate increased grain filling duration in most years for the wet season and only in few years in the dry season. In most cases, the increase in grain filling duration was only 1 - 4 days since grains reached their potential grain weight by that time. In the model, the crop growth is terminated when the grains reach their maximum weight or when the carbohydrate supply is finished or when the crop reaches phenological maturity.

Increase in LAI early in the season associated with increase in relative growth rate of leaf area generally had a positive effect on grain yield in both seasons (Table 10.1). Increased LAI resulted in greater interception of radiation. The consequent increase in growth resulted in slightly higher grain number and hence grain yield. Larger increases were not possible in most cases because crop growth was terminated with the achievement of potential weight of individual grain. Increased leaf area during later stages caused by increased specific leaf area increased yields up to a maximum of 11 - 12%. In 50% of the years, this increase was less than or equal to 8%. ORYZA1 assumes that that when LAI is increased, more nitrogen will be made available to the plant to maintain leaf nitrogen content at the same level as in control crop. However, it is possible that increased leaf area may not have the same N content as in control crops.

A 20% increase in leaf N content resulted in 2 - 12% increase in grain yield while a 20% reduction in maintenance respiration rate of leaves led to a 0 - 5% increase in grain yield (Table 10.1). An increase in shoot:root ratio caused by decreased allocation of carbohydrates to roots increased yields in both seasons. In 50% of the years, the yield increase was 16% or less in the wet season and 8% in the dry season (Table 10.1). Crops with greater leaf:stem ratio caused by relatively increased allocation of carbohydrates to leaves also had higher yields although the increase was always less than 7.2% (Table 10.1). Increase in stem reserves fraction at anthesis increased yields by a maximum of 4% only.

Table 10.1. Effect of a 20% change (decrease in crop development and respiration rates, increase in all others) in input parameters of IR72 on change in simulated grain yield. Simulations were made using 32 years of weather data for Los Baños, Philippines. Only the minimum, median and maximum level of changes are shown.

Parameter	Change in simulated grain yield (%)					
	Wet season			Dry season		
	Min.	Median	Max.	Min.	Median	Max.
Development rate during juvenile period (°Cd^{-1})	−8.7	5.6	23.5	−24.3	4.9	18.3
Development rate during grain filling (°Cd^{-1})	0	9.5	23.4	0	2.0	14.8
Relative growth rate of leaf area (°Cd^{-1})	0	7.2	19.3	0	4.0	14.5
Specific leaf area, (ha leaf kg^{-1} leaf)	3.7	8.0	11.6	2.3	7.5	11.2
Leaf N content (g N m^{-2} leaf)	3.4	8.2	5.5	3.7	7.3	10.2
Maintenance respiration of leaves (kg CH_2O kg^{-1} DM d^{-1})	0	2.3	4.8	0	2.2	4.6
Shoot:root ratio	0.24	16.0	32.5	1.6	7.9	23.9
Leaf:stem ratio	0.9	4.3	7.2	1.5	5.6	6.8
Fraction of stem reserves	0	1.9	4.1	0	1.7	2.2
Spikelet growth factor (number kg^{-1} DM)	0	0	21.0	0	0	11.4
1000 grain weight, (g)	0	0	21.6	0	0	11.4

Increase in sink size due either to an increase in number of spikelets or 1000 grain weight did not result in any increase in grain yield in 50% of the years irrespective of the crop season. In other years, a yield increase up to 21.6% was obtained in the wet season and 11.4% in the dry season. Yield increased only in those seasons where grain weight of control crops had already reached the level of potential grain weight and source was still active. In other years, crop growth was terminated due to thermal time limitations on crop duration.

Overall, these results indicate that the relative importance of different traits may change with season and a 20% change in individual traits can provide a maximum of 16% increase in yield potential in 50% of the years. Greater increase may also be possible in some other years. The magnitude of response to input change varies depending upon the interaction of different traits particularly those related to source-sink balance in different seasons.

Multiple traits

To further examine the opportunities for increasing rice yield potential, an additional analysis was done using additional 'hypothetical' plant types (Table 10.2) for which, more than one model input was varied by 20% simultaneously. Input parameters of IR72 (Kropff et al., 1994b) were modified to obtain the following 'hypothetical' plant types:

1. Increased source capacity (achieved by increase in leaf N content and specific leaf area).
2. Increased source (as in plant type 1) and spikelets (achieved by increasing the spikelet formation efficiency).
3. Increased number of spikelets (as in plant type 2), longer grain filling duration (achieved by reducing crop development rate during grain filling) and higher 1000 grain weight (30 g compared to 25 g of IR72).
4. Greater source (as in plant type 1) and longer grain filling duration (as in plant type 3).
5. Greater source (as in plant type 1), increased number of spikelets (as in plant type 2) and longer grain filling duration (as in plant type 3).
6. Greater source (as in plant type 1), higher 1000 grain weight and longer grain filling duration (as in plant type 3).
7. Greater source (as in plant type 1), increased number of spikelets (as in plant type 2), increased 1000 grain weight and longer grain filling duration (as in plant type 3).

The performance of these plant types was examined by simulating potential growth of rice crops transplanted in the wet season (date of transplanting was 1 July) and the dry season (date of transplanting was 21 January). The simulations were conducted using daily weather data for the last 32 years in Los Baños, Philippines.

The results (Table 10.2, Figure 10.1) showed that there were important differences in yield depending upon the plant type, crop season and the year of planting. All hypothetical plant types yielded higher than IR72. Increased source availability (plant type 1) increased yield by 1.0 to 1.4 t ha^{-1} irrespective of the season (Figures 10.1A and B). This plant type also had larger sink size (grain number) because spikelet formation in the model is dependent on crop growth rate between panicle initiation (PI) and flowering, which was increased by the leaf changes assumed in this plant type. When the number of spikelets increased simultaneously with LAI and leaf N content (plant type 2), median yields exceeded 10.9 t ha^{-1} in the dry season and 8.1 t ha^{-1} in the wet season. This represented a yield increase of more than 1 t ha^{-1} irrespective of the season (Figures 10.1A and B). It is thus evident that increasing number of spikelets (sink) alone would not result in greater yield unless accompanied by simultaneous increase in leaf area and leaf N content (source). Considerable gains in yield potential can also be obtained by increasing the number of spikelets together with higher 1000 grain weight and longer grain filling duration (plant type 3). Almost similar yields were obtained with plant type 4 in the wet season where source capacity and crop development rate during grain filling were changed by 20%. In the dry season, in 75% of the years, relatively more yield was obtained with plant type 3 suggesting that increase in sink size is also essential. Nevertheless, it is clear that grain filling duration definitely needs to be increased to achieve significant increase in grain yield. Simultaneous increase in sink size, source capacity and grain filling duration (plant types 5, 6 and 7) was the best option for quantum increase of yield. Comparison of plant types 5 and 6 indicates that it was not critical whether increase in sink size was achieved through more spikelets or higher 1000 grain weight. Thus, alternative plant types can achieve similar increases in yield potential. Fifty percent of the yields exceeded 9.6 t ha^{-1} in the wet season and 13 t ha^{-1} in the dry season when leaf area, leaf N content, number of spikelets, potential grain weight and grain filling duration were increased simultaneously by 20% (plant type 7, Figures 10.1A and B).

Table 10.2. Characteristics of hypothetical plant types for simulation analysis to compare performance with the standard variety IR72. Also shown are the simulated median yields (t ha^{-1}) obtained in the wet and dry season at Los Baños.

Plant type	Change in input parameter (%)					Simulated grain yield	
	Specific leaf area	Leaf N content	Spikelet growth factor	1000 grain wt	Development rate during grain-filling	Wet season	Dry season
IR 72	0	0	0	0	0	6.9	9.3
1	+20	+20	0	0	0	8.0	10.6
2	+20	+20	+20	0	0	8.1	11.0
3	0	0	+20	+20	−20	8.6	11.4
4	+20	+20	0	0	−20	8.7	10.8
5	+20	+20	+20	0	−20	9.5	12.7
6	+20	+20	0	+20	−20	9.5	12.7
7	+20	+20	+20	+20	−20	9.6	13.2

Is it possible to obtain such a combination of physiological traits in reality? Increased number of spikelets per unit area has already been achieved through introduction of genes from tropical japonicas (Peng et al., 1994). Simultaneously, an increase in 1000 grain weight should also be possible by selecting for high density grains. Grain density, related to 1000 grain weight, is a heritable character (Venkateswarlu et al., 1986). The well-known negative relation between spikelet (grain) number and 1000 grain weight observed in current varieties may not be easy to break unless source capacity is increased. An increased source as simulated in these plant types was achieved through increased leaf N content and leaf area during panicle formation and grain filling stages. In other words, there is a requirement for large green leaves that senesce slowly during grain-filling and yet meet grain N and C demand. Our unpublished results of a recent experiment involving 4 rice varieties and 4 nitrogen fertilizer treatments showed that it is possible to have thinner leaves with relatively higher N content during reproductive stages. Post-anthesis senescence can also be delayed by suitable N management. Increased yields by this approach were demonstrated by Cassman et al. (1993).

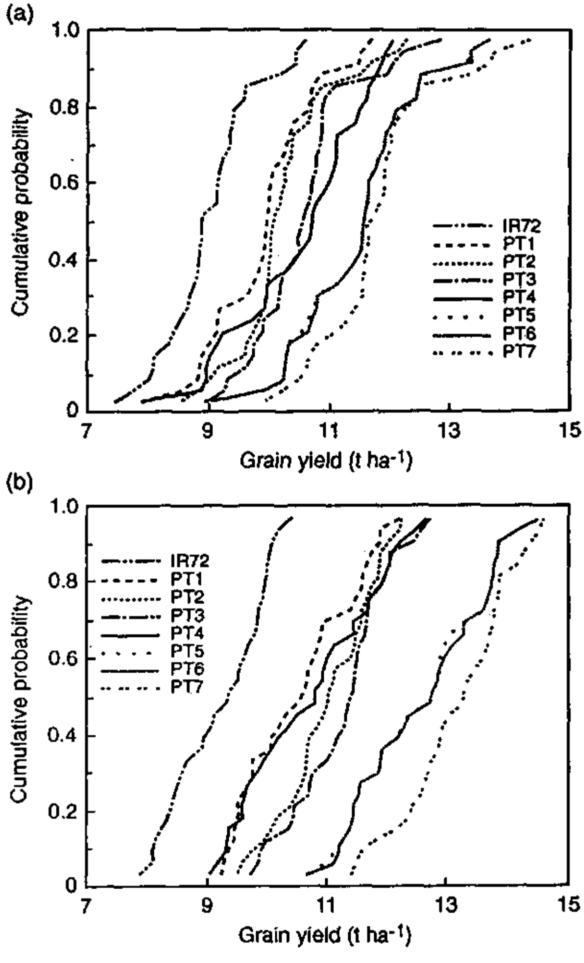

Figure 10.1. Cumulative probability distributions of simulated grain yield for various rice plant types in (A) the wet season and (B) the dry season at Los Baños, Philippines. Plant type details are described in Table 10.2.

The analysis so far has assumed that each of the relevant parameters was changed by 20% from its standard value and each model parameter can be varied independently of the other parameters. In reality, rice germplasm may have much less or much more variation for individual parameters than 20%. For example, simulation results suggest that increasing grain filling duration is essential for a quantum gain in yield potential. But in many rice varieties, the period from flowering to maturity is relatively constant suggesting that there is not much genetic variation available for selection. Although some studies indicate variation in grain filling duration (Senadhira and Li, 1984), critical examination of methodology and source and sink balance is needed. Thus, even if final yield predicted by the model is sensitive to variations in these parameters, their lack of variability places a limitation on the progress that would be made by selecting for these characteristics. Often it is possible to create additional genetic variation in traits. Whether increased variation can be created in the critical model inputs providing yield advantage is not clear at this stage. Other parameters, such as the time from sowing to panicle initiation are much more variable (Vergara et al., 1969) and greater progress would be expected in selecting for such characteristics. But increasing total crop duration may not be practical from a cropping system view point. In addition, the simulation results do not indicate major yield gains by changing duration alone. Increasing total crop duration may result in a decrease in leaf nitrogen content (g N m^{-2} leaf area) and thus growth and yield, unless total leaf N content is increased simultaneously.

The results would also be greatly influenced by the temporal availability of nutrients and water, other management and biotic factors and G×E interactions. Many rice production systems have constraints of nutrients, irrigation and labour. Weeds, insects and diseases reduce yield in most rice environments. There is a need to determine the importance of different physiological traits in region specific agro-environments (Kropff et al., 1995). Lodging has a high probability in tropical environments, particularly in the wet season. Many of these aspects are not considered in crop models. Nevertheless, provided the negative linkages among traits and physiological processes are adequately included in crop models, a systems approach to plant type design can give useful indications as to which characteristics breeders may be able to select for higher yield potential. In the Simulation and Systems Analysis for Rice Production (SARP) Project (Ten Berge et al., 1994), greater efforts are now being made to identify critical plant traits in regional agro-environments and to collect information on genetic variability in these traits.

Assisting Multi-Environment Testing

Breeding lines are generally evaluated across several locations and seasons to determine their adaptation and stability over environments. Rice evaluation trials are conducted in hundreds of locations by the International Network for Genetic Evaluation of Rice (INGER). For example, in the state of Tamilnadu in India, multi-location evaluation of rice is done over a period of 10 years at 100 locations and a variety may be evaluated in as many as 288 experiments before it is released (Palanisamy et al., 1993). Despite such extensive testing it is impossible to cover the whole range of environments. It may often happen that a specific environmental challenge may not be available in natural environments to enable effective discrimination among breeding lines. Simulation models, well characterized in terms of critical physiological traits, together with historical weather data and techniques of risk analysis may be able to be used for environmental characterization of sites and for evaluating G×E interaction (Muchow et al., 1996).

Identification of superior genotypes is generally done by ranking yields of breeding lines and their quality and pest resistance scores relative to control checks. Simulation models can be used to assess the relative performance of breeding lines. The necessary crop inputs can be measured at a few carefully selected sites and the GxE interactions quantified over other sites. Programs such as GENCALC (Hunt et al., 1993) are also available to determine the model input parameters from experimental observations. The methodology can be used to assess the performance of various genotypes across a much wider range of management options than would be possible by experimentation. Palanisamy et al. (1993) used the MACROS model to determine the relative performance of pre-release rice genotypes across the state of Tamilnadu, India. The average simulated ranking of genotypes across locations showed a reasonable agreement with measured values. Out of three best lines identified by simulation two were also selected by the experimentation. Although this experience is encouraging, small differences between lines (say less than 500 kg ha^{-1}), as commonly observed in many well conducted multi-environment trials, are difficult to simulate with crop models because of inaccuracies in measurement of model inputs and the fact that this is approaching limits of model resolution. While such differences may not be statistically significant they nevertheless lead to breeding lines being assigned different ranks. Conventional field trials also encounter stresses such as pests and other management problems which may affect expression of full yield potential. The decision to identify a variety is dependent upon pest resistance score and quality as well. These aspects are not considered in the current modelling effort and may cause differences among observed and predicted genotype rankings.

Interaction of crop models and statistical analysis:

Stability analysis techniques (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966) are used in many breeding programmes to describe the response of genotypes in multi-environment trials. The assumption in these trials is that response of genotypes to change in environment is linearly dependent on site quality. New statistical tools which do not require this assumption, such as additive main effects and multiplicative interaction models (AMMI) (Gauch, 1992) and pattern analysis (Delacy and Cooper, 1990) are being used to discriminate among genotypes and to explain G×E interaction.

It would be useful to see whether crop simulation models are able to replicate GxE interactions as determined by statistical analysis of experimental data. At this stage, however, no multi-environment trials are available for rice where crop input parameters necessary to use crop simulation models are measured. Therefore, in this chapter, we describe an approach to get an idea of the magnitude and complexity of G×E interaction generated by the simulation models. Irrigated grain yield of 26 genotypes was simulated using ORYZA1 over ten locations in Asia (Joydebpur in Bangladesh, two sites at Los Baños in Philippines, Yezin in Mynmar, Pingtung in Taiwan, Nanjing in China, Pattambi, Hyderabad, Cuttack and

Kapurthala in India). The genotypes were 'created' by random combinations of eight crop parameters (leaf N content, fraction of stem reserves, leaf:stem ratio, relative growth rate of leaf area, specific leaf area, spikelet growth factor, and crop development rates during juvenile phase and grain-filling period) (Table 10.3). These parameters were varied within a narrow range to simulate the extent of variation expected in an advanced multi-environment trial.

Table 10.3. Percent change in input parameters in 26 hypothetical genotypes relative to IR72 used to 'represent' physiological variation in an advanced multi-environment trial.

Geno-type	Change in Input Parameter (%)							
	Leaf N content	Stem reserves	Spikelet factor	Leaf:stem ratio	Dev. rate juvenile	Dev. rate pan. dev.	Rel. growth rate of LAI	Specific leaf area
IR72	1.0	0.2	64900	1.0	0.000773	0.000784	0.008	1.0
1	0	0	0	0	0	0	0	0
2	−10.8	−47	−3.1	11	−14.1	−19	0	−4.2
3	8	−37	−21.4	3	3.4	-8.3	12	10
4	−8	45	−2.5	6	−30.7	−19.1	−21.1	−2.7
5	11	−16	3.5	1	3.5	−3.8	1.9	4
6	−6.8	−29	3.7	−11.4	−30.5	2.4	−14.8	−7.8
7	9	−50	3.1	−4	3.9	−14.7	−3.4	−8.5
8	11	−21	3.2	−7.1	−7	−10.3	6.7	1
9	5	36.5	0	−9.8	−13.6	−25.1	5.6	−7.3
10	3	−22	−15.7	−7.3	−13.8	−24.6	14.7	7
11	8	−19.5	−5.2	1	−12.3	−32.5	−10.6	−5.2
12	−8	43.5	12.8	−14.1	−1.6	−23.5	2.4	2
13	8	−4.5	14.8	9	−28.3	−21.3	−7.4	−2.1
14	14	33.5	15.3	13	−9.7	−18.1	−6.5	1
15	−8.9	−0.5	−16.9	2	−15.3	6.1	−0.4	−9
16	5	11	−21	−2.3	−7.8	−6.6	1.6	−3.6
17	1	29.5	−19.7	−10.2	12.9	−5.6	−11.5	−5.6
18	10	20.5	−14.8	−7.4	4.5	−10.7	−3.4	−11.4
19	−4.3	-13.5	−19.3	4	−4.3	−6.1	4.2	9
20	15	−14	−21.3	−9.8	−10.5	−12.4	−7.8	2
21	13	−27	−8.5	7	5	−25.6	6.1	−2.1
22	1	−10.5	6	−3.3	−7.1	−16.1	13.5	1
23	−6.2	17	−7.7	−9.3	6	−12.6	20.4	0
24	3	−18	10.3	−15	−2.1	−14.3	−17.8	−11.2
25	6	−4.5	12.9	−5.9	−21.3	−10.2	−24	−2.5
26	10	7	−7.1	−1.7	−8.2	−30.9	−6.3	2

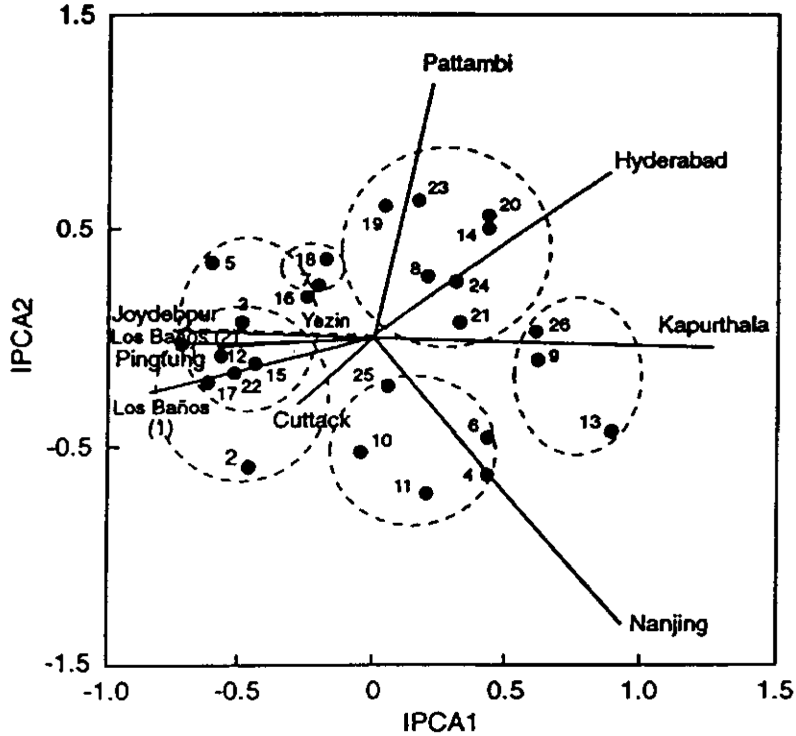

Figure 10.2. Interaction biplot for the AMMI2 analysis of simulated GxE data for 26 hypothetical genotypes simulated over 10 environments (numbered points refer to genotypes described in Table 10.3 and spokes join environmental scores to the origin. IPCA scores are the multiplicative interaction scores for genotypes in the AMMI2 model).

Environmental and G×E effects were of similar magnitude to that of many irrigated INGER multi-environment trials (56% and 14% of total SS). Two multiplicative components accounted for 76% of the G×E interaction. This low dimensionality is not usually seen in experimental data where four or more axes are often needed to account for 50 - 60% of the G×E SS. The AMMI biplot for the first two multiplicative interaction scores displays the genotype and environment interaction scores on the same axes so that relationships can be detected. This is shown in Figure 10.2. It can be seen that genotypes 1,2, 3, 5, 12, 15, 16, 17 and 22 are well adapted to sites Los Baños, Yezin, Pingtung, Cuttack and Joydebpur while genotypes 9, 13 and 26 are well adapted to sites Hyderabad and Kapurthala at the opposite end of the first axis. These two groups of genotypes only differ significantly with respect to crop development rate during juvenile phase. The major difference between Hyderabad and Kapurthala and the opposite group of sites is that they have more radiation and a greater change in temperature over season. Hence, we can deduce that genotypes 9, 13 and 26 with low development rates could take advantage of these conditions at Hyderabad and Kapurthala by extending grain filling period in cooler temperature. On the second axis, it can be seen that the interaction is caused by genotypes 19, 23, 20, 14, 8, 24 and 21 being well adapted to

Pattambi and genotypes 25, 10, 6,11 and 4 being adapted to Nanjing. These two groups of genotypes again only differ significantly in the values of crop development rate during juvenile phase, with the group adapted to Nanjing having the lower values. The sites Pattambi and Nanjing differ significantly in latitude and temperature with Nanjing, the higher yielding site having lower temperature.

Taking the above results as a positive indication that useful aspects of G×E interaction can be simulated by crop models and identified by statistical analysis, we have proposed the strategy shown in Figure 10.3 for increasing the efficiency of METs at IRRI. This strategy uses limited METs data to estimate genotype interaction scores by AMMI analysis for all test genotypes on one hand and to identify groups of genotypes with similar interactions via pattern analysis on the other. Representative genotypes for each group are identified and their performance simulated over a wider range of target environments. The interaction scores for these new environments are estimated from the simulated responses and combined with the genotype scores from the original MET to extrapolate G×E effects over the wider range of environments. Again, because experimental data is not yet available to test this framework, a simulation approach is described here to gauge its usefulness. The simulation results for the 26 genotypes and 10 sites as discussed above were regarded as experimental data. They were subjected to pattern analysis using raw residuals from the additive genotype and environment model as input data. Six genotype groups were identified, these are shown by the ovals in Figure 10.2. One genotype from each group was chosen from the center of the ovals to be the reference genotype representing that group. These reference genotypes were 5, 6, 7, 13, 15 and 23. Data for eight new environments were then generated with ORYZA1 for the same 26 genotypes. These were used to obtain hypothetical G×E effects as residuals from the additive model applied to this new data. The simulated interaction effects for the new sites are taken to represent the unknown interaction effects we would like to estimate by simulation of the reference genotypes. Hence an AMMI analysis with two interaction axes was fitted to the newly generated data for the reference genotypes only. This was used to estimate environment scores for the eight new sites. These scores were combined with the genotype scores from the original 10-site simulation to provide estimates of the interaction effects in the new sites. A highly significant positive correlation of 0.51 was observed between the estimated and simulated interaction effects for the new sites indicating the potential for this type of combination of statistical analysis and crop modelling to extend the range of G×E information. Factors which will affect the quality of estimation of interaction effects are the number of genotype groups in the original data set and the number of reference genotypes used in the modelled data set as well as the degree to which the G×E effects of the new environments are represented in the range of the original set of environments.

These simulations and AMMI analysis results indicate that the crop model is generating meaningful G×E interaction which can be detected and estimated by statistical analysis. Clearly, it cannot generate interactions with factors not included in the model such as diseases and pests and nutrient interactions. This may account for low dimensionality of interaction in the simulated data. The next investigation of interaction between crop models and statistical analysis is to compare the analysis of experimental data with data simulated for the same genotypes and environments. Work is now in progress in the SARP project, in collaboration with regional, national and international germplasm evaluation networks, to evaluate the usefulness of this approach in analysing and interpreting G×E interaction (see also Wade et al., 1996). If we find that simulation is generating the dominant interaction effects, then the potential is indicated for the use of simulation to extend experimental observations of GxE interactions over multiple years or wider geographical conditions.

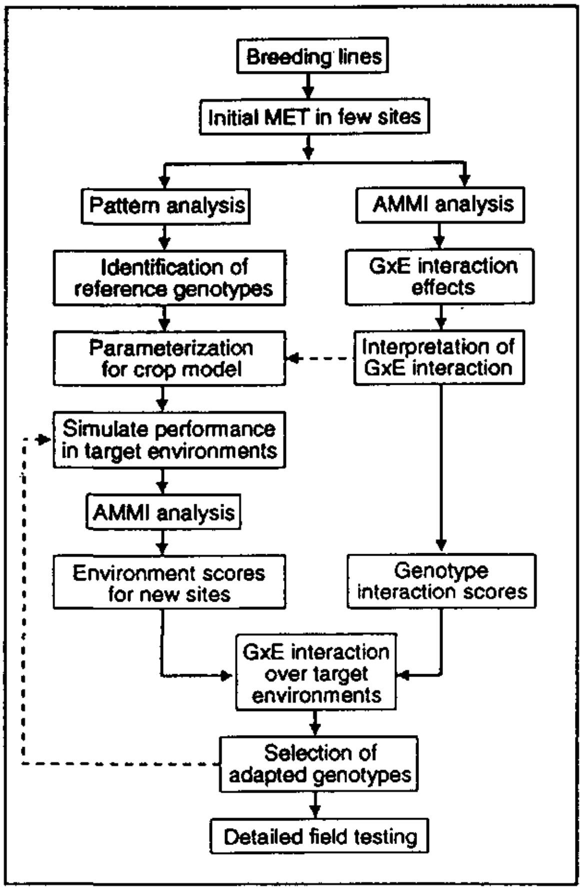

Figure 10.3. A framework for using crop growth simulation models and statistical analysis together to increase the efficiency of multi-environment genotype testing.

Conclusions

Our results show that for breeding for increased yield potential, different approaches may be taken. Changes in individual traits may not provide large increase in yield potential. An optimal combination of source and sink capacity together with increased grain filling duration is needed. Further evaluation is in progress to identify the optimal combinations of traits related to phenology, leaf area development, sink size and their crop management requirements that will result in higher yield in various tropical agro-environments.

Crop simulation models provide useful opportunities to extend detailed physiological knowledge to plant breeding programmes. Together with statistical techniques they provide an integrated system for design of plant types, understanding the causes of G×E interaction and for extrapolating performance of breeding lines.

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11 • General discussion

The rapid increase in population during last few decades has reduced the availability of cropland per person drastically in several developing countries. A larger increase in crop productivity during last three decades ensured that there were no large-scale food problems in these regions. The increasing trend of population still continues in many regions, particularly in South Asia, which may threaten their food security. The world as a whole may be able to produce enough food for meeting everyone's need, but due to social, economic and political reasons, most food will need to be produced in the regions where needed (Rabbinge, 1999). Understanding the yield potential of different regions, quantification of yield gaps and strategies to increase yield potential are, therefore, important issues. Systems simulation tools help us in acquiring insights into these issues. In the previous chapters, applications of crop models in understanding the wheat yield potential in different agro-ecological regions of India and Southeast Asia and in determining strategies to increase rice yield potential have been illustrated. In this chapter, major points emerging from these chapters are reviewed and further discussed. Opportunities for future direction of research are also elaborated.

Yield potential of wheat in India

The results presented in Chapters 4 and 5 have shown that in most regions of India where wheat is currently produced, climatic factors allow a yield potential that is much higher than actual yields. This potential increases with latitude and is related to temperatures during crop season. Regions with greater potential for yield increase with a given amount of input were also identified. For example, results indicate that optimal economic yields in Punjab and U.P. state are similar and larger yield gaps in most districts of U.P. state are due to sub-optimal input use and late plantings. Based on 1990-91 statistics, fully irrigated districts (constituting 1/3 of the total wheat area of the country) alone showed an average yield gap of 1.96 t ha^{-1} and a production gap of 16.2 M tons. If we consider the most recent production statistics, this gap is already reduced to less than one t ha^{-1} in north-western regions and thus to about 8 Mt tons in production. Further increase in yield in these districts will, therefore, be only marginal and slow. These estimates of potential yield and production can have a maximum bias of 10% due to uncertainties in crop, soil and weather input parameters used in the crop simulation model. Research for these regions must now focus on increasing yield potential and input use efficiency. In other regions, such as in eastern India, there is still a large untapped potential for wheat production. Greater focus on these regions in future will help sustain food security.

Although wheat in India is grown in the post-rainy season with very few cloudy days, potential yields show considerable variance due to yearly trends in climatic variability. Delay in sowing results in sharp decrease in grain yield. In general, the higher the yield potential the higher is the loss per day delay in sowing. A large fraction of this could be attributed to delayed sowing time. Statistics show that in Haryana 40% of the wheat is sown much later than the optimal sowing date which is about 15 November (Sinha et al., 1998). Upto 10 -

15% area is sown even later than a month from optimal time. Similarly in Punjab, almost 25% wheat is sown in December. These sowings result in exposure of grain filing period to relatively higher temperatures, resulting in reduced grain filling duration and yield.

Results based on single commodity analysis however may have limitations. In Indo-gangetic plains, most wheat is grown after rice. The latter fetches higher price and thus even if wheat sowings get delayed farmers make more profits per year. There is a need to analyse crop production and profits over the whole farming system which farmers try to maximize.

It is said that yields of rice and wheat have declined over last few years in some parts of north-western India (Sinha et al., 1998). These areas witnessed a large increase in rice-wheat system in the seventies. Because rice generally vacates fields late, particularly basmati rice, wheat sowings get delayed which reduces yields. Comparison of wheat grain yields over the last three decades from such areas, therefore, often gives the impression that yields have decreased.

Our recent unpublished simulation studies have shown that indeed the potential yields of wheat show a small decline even for normal time planted crops (Aggarwal, 1999; unpublished). A significant part of this decline could be ascribed to weather. The data revealed that solar radiation in north-western India over last three decades has declined by about 10%. Similarly, there is an increasing trend of about 0.5-1.5 °C in minimum temperature during the same period at many places. These changes in weather reduce net crop growth and productivity. Perhaps these are artifacts or related to deteriorating performance of weather recording instruments. At the same time, it is also possible that aerosol concentration has continuously increased in urban areas where these observatories are located. Such an increase is known to reduce solar radiation and maximum temperatures and increase minimum temperatures. Such changes can possibly explain yield stagnation/decline in experiments conducted in agricultural research institutions in north-western India, which over time have got surrounded by urban areas. There is a need to analyse if yields of rice and wheat crops have shown any decline in farmer's fields in rural areas.

The magnitude of global warming remains uncertain. Based on the scenarios of IPCC 1990, we have estimated that yield potential of wheat will not be affected in northern wheat belt of India but will be reduced in already warm central regions. Unless, new varieties that are more tolerant to heat evolve, this may result in gradual shifting of wheat towards northern areas or in reduction in area under wheat cultivation. This may have serious consequences on the food security of the region. Even when the uncertainty in climate change scenarios for India is considered, the results show that central regions will be more effected irrespective of the magnitude of global warming (Aggarwal et al., 1999; unpublished studies).

Crop simulation with different amounts of nitrogen and irrigation showed significant effects of the interaction between water and N availability on grain yield particularly at low levels of inputs usage. In order to achieve higher yields there is a need to maintain crops free from water stress a few weeks before flowering and grain filling phases. Application of three irrigations during cropping season produced at least 90% of yield achieved by still more number of irrigations in 75% years. The agronomic recommendation of applying 5 - 6 irrigations in wheat in north-western India (Singh et al., 1985) appears, therefore to be on the high side. Farmers, in general, apply a lot more water because it is free or very cheap in most regions. This results in several ecological problems relating to increased pests, nutrient losses and salinity. Considerable savings in water can result if water-pricing policy is revised and rationalized.

Yield potential of wheat in non-traditional warm areas

Crop simulation models basically deal with genotype-by-environment interactions and hence are very useful tool for assessing the opportunities for introducing a crop in a region where its performance is not well understood. They can assist in prioritizing the goals of the research programmes in such regions. Applications of such a model helped us in quantifying the potential yields of the available varieties in diverse agro-environments of south-east Asia. The model was validated in south Asia and with certain preliminary experiments conducted in south-east Asia. The results presented in Chapter 7 indicated that potential yields exceed 3 t ha^{-1} at all places and increased further with latitude and elevation. At sea level, between equator and 8°N latitude, potential grain yield was 3 t ha^{-1}. It increased to 5 t ha^{-1}at 21°N and 4.5 t ha^{-1}at 10°S latitudes. At 500 m elevation, the potential was more than 5 t ha^{-1} below 5°S and 15°N equator.

In intensive cropping systems, there is always a premium on high-yielding, yet shorter-duration crops. The simulation results indicated that the duration of wheat in south-east Asia is 70 to 100 days, comparable with (or often shorter than) those of other competing crops, indicating that it can fit very well in intensive cropping systems.

While the estimates of potential grain yield are important as a yardstick, the predictions assume all conditions for crop growth to be optimal throughout the entire growth cycle. For example, it is assumed that the crop was timely sown; that there was no water and nutrient stress; and that pests and diseases were absent. Such situations are rare. Realization of the yield potential of the presently available varieties may be limited because of several agronomic constraints. There are many regions in south-east Asia where only limited irrigation or rainfall is available during the dry season. Most of the 30 M ha of rainfed lowland rice remains fallow during the dry season due to lack of irrigation water. Wheat grown in these areas on residual moisture will have limited growth and yield. On the other hand, the majority of areas between 5°S and 5°N latitudes have fewer than two dry months. Since such heavy rainfall is likely to result in waterlogging in most rice soils, wheat in this region will have very poor growth and yield. Nevertheless, there are large tracts of land in the lower latitudes, which have moderate rainfall during the dry season. Here, though the grain yield potential is less, a large part of this could he realized without irrigation. This was also observed in field experiments done in Philippines and Thailand (CIMMYT, 1985). It will be necessary, however, to establish the wheat crop as early as possible under rainfed conditions to take advantage of the stored soil water and growing-season rainfall. Simultaneously, adequate drainage will be required to prevent waterlogging. Converting the puddled, clayey rice soils from anaerobic to aerobic condition is a major and time-consuming undertaking. Establishing a good crop stand in these soils is a serious limitation.

Planting of crops after rice often gets delayed due to the delayed planting of rice (the most common wet-season crop); the use of longer duration, photosensitive varieties; or the existence of a long turnaround time. Such a delay reduces grain yield of wheat in south Asia by almost 50 kg ha^{-1} d^{-1}. This, however, may not greatly affect wheat under irrigated and well-managed conditions in south-east Asia due to relatively small changes in temperatures during the season.

The relatively high humidity and temperature in south-east Asia is favourable for the spread of many diseases. The most common diseases observed in wheat grown in this region are damping-off and foot rot caused by *Sclerotia rolfsii* and *Rhizoctonia solani*, and leaf spot caused by *Helminthosporium* species. *S. rolfsii* is omnivorous, soil-borne, and widely distributed and can survive in the soil for long periods. Its control has been difficult. Rusts and smuts may also be a serious threat if wheat is grown on a larger scale. Several insect pests such as semilooper, pink stemborer, corn earworm, and aphids have been observed to affect wheat growth in the tropics. Unless effective control methods integrating resistance breeding, suitable agronomic practices, and chemical controls are developed, wheat yields on farm will remain low.

Despite reasonable yield potentials, the cost:benefit analysis of growing wheat will ultimately decide the fate of locally produced wheat. The analysis has to be both at the individual farm level and at the country level. Continued interest in domestic wheat production is dependent upon the growing consumption of wheat and wheat products. The policies of the national government can be modified to decrease consumption. At the farm level, the cost of inputs (including labour and land) and expected breakeven yield levels are very important. At the national level, one has to look at the comparative advantage of growing wheat with partially imported inputs (such as fertilizers) vis-a-vis wheat imports.

No crop production programme can be successful and sustainable without local government support. Progress in wheat and rice production during the last two decades in Asia and Latin America has been due to the availability of symphonic packages not only of technology, but also of services such as provision of inputs and government support policies of pricing and marketing (Swaminathan, 1986). Similar packages will have to be made available to the south-east Asian farmer in order to popularize wheat.

Besides production potential, a number of other factors such as global wheat stocks and prices, policies of exporting countries, food aid, trade and tariffs, subsidies, and food marketing policies will decide whether wheat will be grown at commercial level in south-east Asia. Policies of local government, food aid donors, and exporting countries, for example, have generally favoured investment in marketing, storage, and processing of imported wheat in several tropical countries. This situation in Nigeria (where annual wheat imports exceed 1.5 M ton and where there has been 10% annual growth in consumption of wheat products) was incisively labelled as the 'wheat trap' (Andrae and Beckman, 1983). It will be a long struggle before south-east Asia becomes free of a similar trap and is able to produce indigenous wheat.

Higher yield potential: Design and evaluation of new plant types

Increasing yield potential is one of the principal objectives of crop breeding programmes. This is very important in several Asian regions because the irrigated regions on which their food security has been so much dependent are now showing only small yield gaps. A major activity in this is to conceptualize plant type designs and identification of genetic donors for the important traits. Breeders spend considerable time and effort in conceptualizing plant types (Hunt, 1993). Donald (1968) sparked off physiological research on ideotypes, today several of them have been proposed by different scientific groups for major crops. But, not many breeders practiced ideotype breeding because of lack of convincing demonstration of the importance of a specific trait, large number of traits (as against one trait-yield), limited genetic variability in suitable donors and pleiotropic effects (Marshall, 1991). The problem gets confounded with the difficulty in screening methods for some of these traits. Molecular approaches may gradually become available for marker-aided selection for yield components and other quantitative traits (Bennet et al., 1994). The availability of tissue culture techniques such as embryo rescue, protoplasm fusion, which alone or in combination with genetic transformation techniques now allows breeders to exploit genetic variability even from secondary and tertiary gene pools.

Crop breeders have always selected for several morphological features that effect growth, development and yield. However, ideotypes although exploiting upon morphological features should be based on sound understanding of underlying physiological and biochemical processes associated with morphological changes. An inter-disciplinary group of scientists short-listed several key traits for increasing yield potential in cereals (Cassman, 1994). The key ones are: increased specific leaf nitrogen (SLN), rate of photosynthesis per unit SLN, optimization of light interception, reduced respiratory losses and delayed senescence during grain filling, greater crop growth rate during reproductive stages, reduced wasteful tillering to increase sink size, and a slower rate of individual grain filling to extend filling duration. Research experiments for detailed physiological and molecular investigations of these traits having feedback and inter-relationships would be complex, expensive and take long time to deliver. Crop simulation models integrate detailed physiological and morphological knowledge in explaining yield formation in environments varying in physical, biological and agronomic factors and, therefore, offer opportunities to extrapolate the current knowledge of eco-physiology to determine the optimal level of complex traits for increasing yield potential. The models may also be useful for examining hypotheses and for setting breeding goals for different traits using historical weather data and techniques of risk analysis. Sensitivity analysis of the model parameters is analogous to the creation of genetic isolines since only one parameter is changed while keeping the rest of the plant characteristics constant.

A methodological framework for using crop models in the design and evaluation of plant types has been proposed in this thesis (Chapters 8-10). This approach requires a crop simulation model that has been well evaluated in the target environment. The critical crop parameters are determined by means of a sensitivity analysis of traits. When tried in rice, it indicated that any individual trait can not provide large advantage in increasing yield potential and simultaneous increase in specific leaf nitrogen particularly during grain filling (stay green), sink capacity and most importantly, grain filling duration are important for increasing rice grain yield potential. The results also indicated that relative importance of traits changes with season and year. By using historical weather data of 30 years for the target environment, it was also possible to simulate the probability of higher yields in climatically variable tropical environments and to determine alternate options for similar increase in yield potential.

An alternate simulation approach can be used to construct hypothetical varieties with variation in one or many traits. Monte Carlo simulation technique, commonly used in quantitative population genetics studies (Crosby, 1973) is applied for creating such varieties. In this approach, different traits are considered to be stochastic in nature. A large number of varieties can be constructed, each of which is unique in its trait 'makeup'. These varieties thus mimic the random segregation behavior of progeny for different characters when two parents are hybridized. The yield of such hypothetical varieties is simulated for the target environment. The results then indicate the importance of different traits in a specific environment as well as set the breeding goals for individual traits.

Application of such a methodology in rice showed that IR72, the check variety, has large yield potential that can be realized with better N management alone. No trait individually or in combination with others provides more than 5% advantage in yield in the level of management practiced by breeders. Another important conclusion of this simulation study has considerable implications for the breeding methodology. At the level of management practiced currently in breeders plots, search for higher yield potential may remain elusive even though the germplasm being screened may possess traits for higher yield potential. These traits need a better N environment in order to express their full potential. In such environments, increasing sink capacity is necessary and this can be obtained by either increasing the length of the panicle formation phase or by increasing the spikelet growth factor or by higher potential grain weight. Variability in all three of them is well known. In addition, there is a need to increase sink capacity (already achieved in IRRI's new plant type), maintain high leaf N content and grain filling duration.

IRRI is now concentrating efforts on developing 'super rice' varieties with 13 - 15 t ha^{-1} yield potential (IRRI, 1989). This ideotype has low tillering capacity with 3 - 4 panicles per plant, no unproductive tillers, 200 - 250 grain per panicle, 90-100 cm tall, sturdy stems, vigorous root system, multiple disease and insect resistance, 110 - 130 days growth duration and a harvest index of 0.6. Breeding lines with characteristics similar to these are now available. These lines, based on the tropical japonicas, have semi-dwarf stature, sturdy stems, dark green and thick leaves, 8 - 10 productive tillers when grown at low densities, no unproductive tillers and 150 - 200 grains per panicle. Greater sink capacity has been established in these plant types by increased spikelet number. There is, however, a need to build up strategy to increase harvest index to 60% in the new plant type. Greater harvest index is generally a result of higher grain filling duration and leaf N concentration during filling (stay green), and of course, sink capacity. Boote and Tollenaar (1994) concluded that the filling duration is the most likely trait to account for past, present and future increase in harvest index and yield potential. Variation in rice grain filling duration is not well known in rice (Yoshida, 1981; Dionora and Kropff, 1995) although is documented in several other crops (Boote and Tollenaar, 1994). Greater efforts are now being made to determine variability in this trait in rice as well (Khush, personal communication). Insect and disease resistance, and suitable grain quality still needs to be built in these lines.

Our simulation results, however, indicate that unless the agronomic management is optimized, time available for grain filling duration is extended and leaf N is maintained at a relatively higher level during filling period, it is hard to expect increase in yield potential. Preliminary agronomic experiments done with these new lines are confounded by pest problems, therefore, it is difficult to draw conclusions about the success of the ideotype strategy adopted as well as to test the validity of simulation results in field environment.

Multi-environment trials to evaluate the performance of a genotype are expensive and need several crop seasons, sites and years to understand genotype by environment (G×E) interactions. Despite extensive testing done with new genotypes using the conventional approach, it is impossible to cover the whole range of environments. A specific environmental challenge may not be available in natural environments in specific years to enable effective discrimination among breeding lines. Since the systems approach integrates different components of agro-ecosystems, it can play a great role in increasing the efficiency of plant breeding process, in particular understanding and extrapolating G×E interactions. Crop models together with GIS can facilitate biological characterization of the physical environment and thus define key environmental domains for which improved varieties are to be developed. Alternatively, the same methodology can be used to determine the adaptation domains of genotypes. A modelling approach can also provide estimates of yield probability in target environments based on our understanding of G×E interactions. Such studies can help in reducing the number of sites/seasons required for field evaluation and thus increase the efficiency of the whole process of variety development. Often there is some uncertainty in model input parameters, which affects the reliability of simulated absolute yields. However, crop models adequately describe the relative trends caused by environmental variations. This is of considerable use in the process of cultivar selection where ranking of grain yields is the method used to determine the relative superiority of a genotype rather than the absolute yield values. Examples of these approaches are provided in Chapter 10.

It can be concluded that simulation models can greatly assist in evaluating the suitability of the plant types for higher yield potential and in suggesting alternate ones. They can also help at the same time in fine tuning the required management practices for the best expression of desired traits, thus increasing the efficiency of crop improvement programmes. In these simulation studies, the level of genetic variation available in the germplasm for the sensitive parameters is determined from the literature or measured in available germplasm. Alternatively, options to increase variability by genetic means need to be assessed. It is important to determine the range and the boundaries of this variation, in particular in the parents used in the crossing programmes. Simultaneously, it must be assessed if such traits are heritable and if there are associated pleiotropic effects. Lodging, and pests and diseases increase severally in tropical environments when N application is increased. It is likely that current management practices of moderate N application have been adopted to overcome these constraints. There is a need to examine the 'trade-off trap' between yield loss due to pests and lodging, and the increased yield potential due to higher N application to determine if higher yield potential is really possible in field environments.

While it seems that the current models are not able to accurately explain fully genotypic differences due to inadequate considerations of all traits and their feedbacks, it must be highlighted that such an endeavor would also lead to the requirement of measuring much larger number of traits. There is a trade off between simplicity in model's structure and parameters versus the detail in the model and the associated number of parameters. Crop physiologists and geneticists need to define and measure minimum number of efficiently measurable genetic parameters to characterize a genotype.

Many of the earlier limitations in greater application of physiology in plant breeding process still exist. The issue of physiological methodology needed for precision and useful simulations versus the requirements of an efficient screening methodology for large number of genotypes remains unresolved. There is a need to link many of the physiological criteria for yield potential/adaptation with easy to measure/score characteristics. For example, chlorophyll meters can be used to rapidly determine the leaf nitrogen content, generally difficult to estimate in a large number of varieties. Simulation models should also be made more robust in structure to account for existing knowledge and feedbacks. Pilot studies are also needed in conventional field trials to verify the results of simulation studies, to determine the extent of genetic variation, heritability, pleiotropy, and the cost of altering a desired trait. It is this lack of complete physiological understanding that may restrict progress. Nevertheless, provided this information is made available and the negative linkages among traits and physiological processes are adequately included in crop models, a systems simulation approach can give useful indications to which characteristics breeders may be able to select for higher yield potential and stability in different agro-environments.

Future perspectives

Food security involves access at all times to the food required by every individual and household for a healthy and productive life. Thus, by definition it has both biophysical and socio-economic connotation. First, there should be biophysical capability of the land to produce food of the quality and quantity required by the people and then they should have purchasing power to access this. Estimates of food demand and supply for the entire population of different regions have long been made. These estimates differ depending upon methodology used by the author. Most of these studies point out that the world has a whole can produce enough for everyone, yet several regions particularly south Asia will face shortages starting soon (Brown and Kane, 1994; Penning de Vries et al., 1995). The results presented in this thesis, however, indicate that there are large tracts of land, for example in eastern and central India, where potential yields and yield gaps are high which can be tapped to supplement food supply. If we assume an average potential yield of 6 t ha^{-1} for vast majority of Indian wheat producing region, it is obvious that the total food grain production could more or less be doubled. The pessimistic estimates of food deficit may not be correct also due to recent surge in economic growth in several developing countries, particularly India and China, freer trade, and possible technological breakthroughs such as due to biotechnological applications and integrated pest management in future.

Limits to food production may, however, reach much earlier than indicated by the biophysical studies such as ours due to socio-economic or political constraints. Increased food production without increase in area would need intensification and thus greater resource use. Are these resources available? Availability of water supply for irrigation may be a major constraint for increasing food production in several regions of the world. Our recent studies have shown, for example, that the Haryana state in northwestern India although capable of theoretically producing 68 M tons of cereals can not produce more than 16 M tons due to constraint of irrigation water (Aggarwal et al., 2000). Additional issue is the availability of other purchased inputs such as quality seeds, inorganic fertilizers and pesticides, which need capital. Even if resources were to become available, highly intensive agriculture may lead to problems of environmental degradation (Sinha et al., 1998).

Food security also needs to be considered at different scales- global, national, regional, household and then individuals. Food availability at any one scale is not a guarantee for food security at another scale. In order to correctly estimate such balances/imbalances at different scales, it is necessary that our simulations are further expanded and an integrated and validated methodology involving both biophysical and socio-economics be used. The simulation analysis reported in this thesis was done at field as well as regional scale. While validation of the crop model was done at the experimental field scale, no validation could be done in farmers fields or any large region. This is largely because the input data needed at these scales in terms of crop coefficients, soil and weather were not available. The extrapolation of results from field scale to the region was done with simplistic assumptions on spatial variability of soil characteristics, sowing dates, and costs of grain and N in different regions. Recently, we have attempted to validate WTGROWS in farmers fields as well as for different regions across India (Kalra et al., unpublished) based on inputs derived from published soil maps, irrigation intensity, sample surveys of sowing dates and actual fertilizer use by district. These simulations have shown that the crop model was capable of simulating yield trends over past 15 years for most agro-climatic regions of India. The absolute simulated values were, however, generally higher by 10 - 20% than actual yields because spatial and temporal availability of irrigation, biotic constraints, problem soils, harvesting and processing losses and costs were not considered in the analysis. Attempts are now being made to prepare such a database that will enable us to determine realistically yield and production potential of the whole country.

Agricultural stakeholders such as farmers and policy makers are interested to find optimal agricultural land use plans that can meet the goal of maximising food production as well as maximise employment and income from agriculture while minimising biocide residues, N losses and ground water withdrawal. Information, therefore, needs to be generated to determine the consequences and trade-offs of different sets of policy aims on agriculture. The economically viable optimal solutions should be based on the consideration of the biophysical potential of the resources available and the socio-economic constraints. Thus, a systems approach is needed where it is possible to translate policy goals into objective functions integrated into a biophysical land evaluation model. We have recently started developing a methodology based on symphonic use of simulation models, GIS, remote sensing and interactive multiple goal linear programming to deal with most issues encompassing food security in a comprehensive manner (Aggarwal et al., 2000).

It can be concluded that crop simulation models are important tools for estimating food security of a region. In many Asian environments, soils are relatively poor, nutrient use is low, pest control is inadequate and harvesting and processing losses are significant. Under such stresses, it is generally difficult to quantify the genetic yield potential as well as to know the precise and relative importance of various yield-reducing and -limiting factors. To correctly estimate the opportunities for production, these estimates need to be supplemented by a more detailed analysis of other factors not yet included in the simulation models. There is an urgent need to develop high quality databases relating to different aspects of the agro-environment. The Government of India has recently set up database centers in each district to collect primary data on soils, weather, land use and crop productivity besides other activities such as urban development, education, water resources and health. These centers are connected via a satellite network, NICNET, based in New Delhi. Such databases will be extremely useful for strategic and tactical decisions relating to eco-regional development and for the assessment of food security.

Uncertainties associated with systems tools and their consequence is generally raised as a major limitation to wider application. Efforts are definitely needed to improve precision. However, at the same time, we must remember that decision-making processes based on field experiments often have uncertainties due to inadequate understanding and lack of appropriate data (where the so-called systems simulation is not used). And yet still have to make decisions. We need to understand and evaluate if the application of systems approaches increases, or decreases or does not effect uncertainty in our decisions. We do not have a perfect understanding of agricultural systems now and perhaps may not ever have. With current emphasis on sustainable eco-regional development and the free market economy, breeding objectives would rapidly be changing. Raising the yield potential may not be the key question; rather, economic and environmental costs associated with different levels of yield potential may be asked. The systems approach, with its well-developed analytical framework, databases, and powerful simulation models, will be handy to provide answers to many of the queries in a relatively shorter time frame.

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Summary

Increase in cereal production during last three decades made most of the Asian region self-sufficient and contributed tremendously to their food security. The later, however, is now at risk due to increased demand of continuously increasing population. It is, therefore, important to know how much additional cereals, particularly the staple rice and wheat, can be produced by different regions of Asia to meet the increasing demand. In case of population rich and low income regions of Asia, it is also important to know where and at what cost this can be produced with current technology and what alternate technologies will be needed to meet the desired production targets. In this thesis, the goal is to document the applications of crop simulation models for quantifying yield potential of wheat and rice in selected parts of tropics and sub-tropical regions of Asia as affected by climatic factors, genotype, inputs and management practices at field as well as regional scale. The more specific objectives were a) to simulate the wheat yield potential and gaps in diverse agro-climatic regions of India, b) to use systems simulation to explore opportunities for growing wheat in south-east Asian tropics, and c) to develop a crop simulation based framework for design of plant types for increasing yield potential.

A mechanistic crop growth simulation model -WTGROWS (WheaT GROWth Simulator)- was developed to evaluate the effects of climatic variables, genotype, agronomic management including water and nitrogen availability on crop growth, development, water and nitrogen use, and productivity of wheat. The model written in PCSMP simulates daily dry matter production as a function of solar radiation, maximum and minimum temperatures, and water and nitrogen stresses. Crop aspects of the model are arranged in submodels covering development, photosynthesis, respiration, carbohydrate partitioning, dry matter production, leaf area, grain growth and transpiration. A soil water balance model is attached to simulate water uptake and to determine water stress. Another submodel determines nitrogen uptake, distribution and nitrogen stress. Various crop processes are affected by water and nitrogen stresses. This model is described in Chapter 2.

The performance of WTGROWS was tested against a large number of independent data sets collected by several authors over a large period of time. In general, model predicted crop duration, leaf area index and grain yield realistically in potential production environments. Standard error of grain yield prediction was 11.3% of the observed mean grain yield. The agreement between simulated and measured yield, dry matter production, evapotranspiration and N uptake established the model's robustness in predicting climatically potential crop growth and yield.

Deterministic crop growth models require several inputs relating to crop/variety, soil physical properties, weather and crop management. The input values used could be significantly uncertain due to random and systematic measurement errors and spatial and temporal variation observed in many of these inputs. Often soil and weather data are approximated using GIS and/or weather generators. In Chapter 3, total uncertainty in simulated yield, evapotranspiration and crop N uptake has been quantified considering

uncertainties in crop, soil and weather inputs, The uncertainty in each input was represented by a statistical distribution of values based on literature review, actual measurement and subjective expert judgment. The Monte Carlo simulation technique was used to analyse total uncertainty. The results showed that uncertainties in crop, soil and weather inputs resulted in uncertainty in simulated grain yield, ET and N uptake which varied depending upon the production environment. Uncertainties in outputs increased as the production system changed from a potential production level to a level where crop growth was constrained by limited availability of water and nitrogen. There was an 80% probability that the bias in the deterministic model outputs was always less than 10% in potential and irrigated production systems. In rainfed environments this bias was larger. The bias in simulated outputs was less than or equal to model error. Most of the uncertainty in outputs caused by variable soil, crop and weather inputs could be represented if the outputs were determined using fixed soil and crop data, and a large series of weather data. In potential and irrigated production systems, inputs relating to crop photosynthesis and leaf area estimation had a large 'uncertainty importance'. Uncertainties in soil N inputs and vapour pressure were also of large importance in irrigated environments. In rainfed environments, uncertainties in soil and weather inputs were dominant and crop parameters had only limited 'uncertainty importance'. The implications of these results in estimates of potential and rainfed productivity, database development and in guiding refinement of models are discussed in Chapter 3.

Crop simulation with different amounts of nitrogen and irrigation showed significant effect of interaction between water and nitrogen availability on grain yield particularly at low levels of input usage. In order to achieve higher yields there is a need to maintain crops free from water stress few weeks before flowering and grain filling phases. Application of three irrigations during crop season produces at least 90% of yield achieved by still more number of irrigation in 75% years. The amount of N fertilizer applied to crops should have a close link to the amount of irrigation and should consider climatic variation as well. The significant interaction effects of irrigation and nitrogen on wheat productivity and substitution of each other to a certain extent as indicated by crop simulation is also suggested by field experiments. This demonstrates the capability of the simulation approach in replicating qualitative as well as quantitative results of field experiments. These results are described in Chapter 4.

The model was applied to simulate potential growth of wheat in different regions. Simulated potential grain yield varied between 2.56 and 8.25 t ha^{-1} depending upon location. In a large number of districts spread over the states of Punjab, Uttar Pradesh (U.P.), Bihar, Assam, Rajasthan, and Madhya Pradesh (M.P.), potential wheat yields were 7 t ha^{-1} or more. Most districts in U.P. have a yield potential between 6 to 6.5 t ha^{-1}. The potential yield was between 5 and 6 t ha^{-1} in middle latitudes and states of West Bengal and M.P. Economically optimal levels of N fertilizer application in irrigated environments were estimated for all locations based on current price ratios of N fertilizer and grain, native soil fertility, simulated crop response to N fertilizer and other costs related to transport, harvesting and market forces. A comparison of optimal and actual N applications showed that in Ludhiana district of Punjab, N application is more than the simulated optimal whereas in other districts it is at par or lower. The estimated yields corresponding to the profit-maximizing amount of N application were generally 200 to 500 kg ha^{-1} lower than the potential yield irrespective of the location. The small difference between potential and optimal economic yield is due to distorted but favourable price ratios at present. In rainfed environments, optimal economic yields would be still lower.

At most locations, there was a large yield gap. In irrigated regions of north-western India, the main wheat belt, the mean yield gap was between 1 and 2 t ha^{-1}. It was more than 2 t ha^{-1} in remaining wheat growing areas. Almost 35 - 50% of the gap could be ascribed to delayed sowing, common in a number of districts. Factors such as limited and timely availability of irrigation and fertilizers, cropping pattern and access to credit and other services are some of the other principal causes of yield gaps. The results on potential yields and yield gaps are described in Chapter 5.

An assessment of the impact of climatic change on productivity of Indian wheat was made in Chapter 6. A one degree increase in temperature throughout the crop season will have no effect or slightly increase productivity in irrigated as well as rainfed environments, particularly in northern India wheat belt. A two degree increase in temperature will reduce potential yields but will have small effect on irrigated yields in northern India. Evapotranspiration will be significantly reduced in changed climate. Relatively, the effect of climate change will be more pronounced in central India where yield potential is already low. The crop responses to climate change are related to the effect of temperature on crop duration.

In south-east Asia wheat is currently not produced. The entire domestic demand is met by importation at a huge cost. The Governments of this region are very keen to know if wheat can be grown in this region and at what locations. Traditional agronomic trials will take several years to determine this. Using a simple crop growth simulation model, the production potential of wheat for various regions of south-east Asia has been determined. These results are described in Chapter 7. The locations that will meet the water requirement of the crop solely by rainfall were also identified. Whether wheat can fit in the existing rice based cropping system has been evaluated.

Increasing yield potential is one of the principal objectives of crop breeding programmes. This is very important in several Asian regions because the irrigated regions on which their food security has been so much dependent are now showing only small yield gaps. Crop simulation models integrate detailed physiological and morphological knowledge in explaining yield formation in environments varying in physical, biological and agronomic factors and, therefore, offer opportunities to extrapolate the current knowledge of eco-physiology to determine the optimal level of complex traits for increasing yield potential. The models may also be useful for examining hypotheses and for setting breeding goals for different traits using historical weather data and techniques of risk analysis. Sensitivity analysis of the model parameters is analogous to the creation of genetic isolines since only one parameter is changed while keeping the rest of the plant characteristics constant.

A large number of trials are conducted every year at many locations in India where rice and wheat varieties of different maturity groups are grown in different combinations to identify suitable varieties. We used WTGROWS to determine optimal crop duration and flowering time of irrigated wheat in few typical rice-wheat areas of India (Chapter 8). The response of six early, medium and late maturing varieties, assumed to vary in their heat units requirement for the phase- seedling emergence to anthesis was studied. The anthesis dates when grain yields were between 95% and 100% of maximum grain yield were taken to represent the optimal dates. The results showed that for normal sowing dates (15 November), the most suitable varieties are early maturing types in areas such as Punjab, medium maturing types in environments of New Delhi and Uttar Pradesh and late maturing types in West Bengal and Bihar. The optimal duration of variety varied with year-to-year climatic variability.

A methodological framework for using crop models in the design and evaluation of plant types has been proposed in this thesis (Chapters 9-10). This approach requires a crop simulation model that has been well evaluated in the target environment. The critical crop parameters are determined by means of a sensitivity analysis of traits. The approach has been illustrated for rice in Chapter 9. It indicated that any individual trait can not provide large advantage in increasing yield potential and simultaneous increase in specific leaf nitrogen particularly during grain-filling (stay green), sink capacity and most importantly, grain filling duration are important for increasing rice grain yield potential. The results also indicated that relative importance of traits changes with season and year. By using historical weather data of 30 years for the target environment, it was also possible to simulate the probability of higher yields in climatically variable tropical environments and to determine alternate options for similar increase in yield potential.

An alternate simulation approach can be used to construct hypothetical varieties with variation in one or many traits. Monte Carlo simulation technique, commonly used in quantitative population genetics studies is applied for creating such varieties. In this approach, different traits are considered to be stochastic in nature. A large number of varieties can be constructed, each of which is unique in its trait 'makeup'. These varieties thus mimic the random segregation behavior of progeny for different characters when two parents are hybridized. The yield of such hypothetical varieties is simulated for the target environment. The results then indicate the importance of different traits in a specific environment as well as set the breeding goals for individual traits. Application of this methodology in rice showed that IR72, the check variety, has large yield potential that can be realized with better N management alone (Chapter 10). No trait individually or in combination with others provides more than 5% advantage in yield in the level of management practiced by breeders. Another important conclusion of this simulation study has considerable implications for the breeding methodology. At the level of management practiced currently in breeders plots, search for higher yield potential may remain elusive even though the germplasm being screened may possess traits for higher yield potential. These traits need a better N environment in order to express their full potential. In such environments, increasing sink capacity is necessary and this can be obtained by either increasing the length of the panicle formation phase or by increasing the spikelet growth factor or by higher potential grain weight. Variability in all three of them is well known. In addition, there is a need to increase sink capacity, maintain high leaf N content and grain-filling duration.

Multi-environment trials to evaluate the performance of a genotype are expensive and need several crop seasons, sites and years to understand genotype by environment (G×E) interactions. Despite extensive testing done with new genotypes using the conventional approach, it is impossible to cover the whole range of environments. Crop models adequately describe the relative trends caused by environmental variations. This is of considerable use in the process of cultivar selection where ranking of grain yields is the method used to determine the relative superiority of a genotype rather than the absolute yield values. A modelling framework is described in Chapter 10 for using crop simulation models and statistical analysis together to increase the efficiency of multi-environment genotype testing. Detailed multi-environment trials are not available where input parameters necessary to use crop simulation models are measured. Irrigated grain yield of 26 genotypes was simulated using ORYZA1 over ten locations in Asia to mimic a MET. The genotypes were 'created' by random combinations of eight crop parameters, which were varied within a narrow range to simulate the extent of variation expected in an advanced multi-environment trial. Environmental and G×E effects were of similar magnitude to that of many irrigated INGER multi-environment trials. The simulations and AMMI analysis results indicate that the crop model is generating meaningful G×E interaction, which can be detected and estimated by statistical analysis. The next investigation of interaction between crop models and statistical analysis is to compare the analysis of experimental data with data simulated for the same genotypes and environments.

In Chapter 11, the results presented in previous chapters are integrated in relation to three major objectives of this thesis. The limitations of the study and future opportunities are discussed.

Samenvatting

Door de sterke toename van de graanproductie in de afgelopen decennia is het grootste deel van Azië zelfvoorzienend geworden. Echter, door de sterke bevolkingsgroei in Azië nemen risico's met betrekking tot de voedselzekerheid toch toe. Daarom is het belangrijk te weten hoeveel extra rijst en tarwe er in de verschillende regio's in Azië, geproduceerd zou kunnen worden om aan deze toenemende vraag naar voedsel te kunnen voldoen. Omdat in veel regio's de inkomens laag zijn en de bevolkingsdichtheid hoog, is het nodig te berekenen wat de kostprijs is van de graanproductie gebaseerd op de huidige technologie en ook op alternatieve technologieën die nodig zullen zijn om de productiedoelstellingen te kunnen realiseren. De algemene doelstelling van dit proefschrift is het kwantificeren van potentiële opbrengst van tarwe en rijst voor een aantal regio's in Azië (tropen en subtropen) op grond van de effecten van klimaatsfactoren, genetische eigenschappen en teeltmaatregelen op veldschaal en regionale schaal met behulp van simulatiemodellen. De specifieke doestellingen zijn a) het simuleren van de potentiële opbrengst van tarwe voor verschillende agro-klimatologische zones in India b) het toepassen van systeemanalyse en simulatie om na te gaan wat de mogelijkheden zijn om tarwe te produceren in Zuidoost-Azië en c) het ontwikkelen van een kader om nieuwe rassen met een hogere potentiële opbrengst te ontwerpen.
Het gewasgroeisimulatiemodel WTGROWS (WheaT GROWth Simulator) werd ontwikkeld om de effecten te simuleren van klimatologische variabelen, raseigenschappen en teeltmaatregelen op de ontwikkeling, het water- en stikstofgebruik en de productiviteit van tarwe. Het model is geschreven in PCSMP en simuleert de dagelijkse drogestofproductie als een functie van straling, maximum en minimum temperatuur en water- en stikstof als beperkende factoren. Het gewasgroeimodel bestaat uit submodellen voor de ontwikkeling, de fotosynthese, de respiratie, de verdeling van assimilaten, de drogestofproductie, de toename van het bladoppervlak, de korrelgroei, de verdamping van het gewas, de bodemwaterbalans en bodemstikstofbalans. Verschillende gewasprocessen worden door N- en watertekort beïnvloed. Het model is beschreven in Hoofdstuk 2.

Het model WTGROWS werd getoetst met vele onafhankelijke datasets. De fenologische ontwikkeling, LAI en korrelopbrengst onder potentiële productieomstandigheden werden goed gesimuleerd door het model. De gemiddelde afwijking van de voorspelde korrelopbrengst was 11,3% van de waargenomen korrelopbrengst.
Deterministische gewasgroeimodellen hebben inputs nodig met betrekking tot gewas/raskenmerken, bodemeigenschappen, weersgegevens en teeltmaatregelen. Meetfouten (*random* en systematisch) en ruimtelijke en temporele variatie in veel inputgegevens leiden tot onzekerheid in de waarden van de inputvariabelen van het model. Vaak worden bodem- en weersgegevens geschat met behulp van GIS en/of weergeneratoren wat leidt tot extra onzekerheid. In Hoofdstuk 3 wordt het effect van deze onzekerheden in inputgegevens op de gesimuleerde opbrengst, evapotranspiratie en N-opname door het gewas gekwantificeerd. De onzekerheid voor elke inputvariabele werd gekarakteriseerd door een statistische verdeling van waarden die zijn gebaseerd op literatuurgegevens, metingen en subjectieve expertschat-

tingen. De Monte Carlo simulatietechniek werd gebruikt om de onzekerheid in de gesimuleerde opbrengst te schatten. De onzekerheid in gesimuleerde korrelopbrengst, evapotranspiratie en N-opname varieerde afhankelijk van de productiesituatie. Onzekerheden in de outputs namen toe als het productieniveau afnam van potentieel naar water- en/of N-gelimiteerd. De kans op een afwijking in het modelresultaat van minder dan 10% in potentiële groeisituaties was 80%. In regenafhankelijke systemen was de afwijking groter. De variabiliteit in outputs door variabiliteit in gewas-, bodem- en weersgegevens werd ook gesimuleerd met vaste bodem- en gewasgegevens voor een lange tijdreeks aan weersgegevens. In potentiële groeisituaties hadden parameters gerelateerd aan gewasfotosynthese en bladoppervlakteontwikkeling het grootste effect op de variabiliteit. Onzekerheden in N-inputs en luchtvochtigheid waren ook van belang in geïrrigeerde systemen. In regenafhankelijke systemen waren bodem- en weersgegevens het meest belangrijk. Gewasparameters hadden in deze situatie minder invloed. In Hoofdstuk 3 worden de implicaties van deze resultaten voor het berekenen van potentiële productie en water-gelimiteerde productie, databaseontwikkeling en het aansturen van modelverfijning en modelverbetering besproken.

Gewasgroeisimulaties met verschillende hoeveelheden N en irrigatiewater lieten vooral bij lage inputniveaus een significant interactie-effect van N en water op de opbrengst zien. Om hoge opbrengsten te realiseren was het nodig om het gewas vanaf enkele weken voor de bloei tot afrijping vrij van watertekort te houden. Met 3 irrigaties werd, in 75% van de jaren, minstens 90% van de potentiële opbrengst gerealiseerd. De hoeveelheid toegediende N moet aangepast zijn aan de hoeveelheid irrigatiewater en zou ook aangepast moeten worden aan de weerssituatie. De door het model gesimuleerde significante interactie-effecten van irrigatiewater en N op de productiviteit van tarwe en de uitwisselbaarheid van de verschillende inputs is ook gevonden in veldexperimenten. Dit geeft aan dat het model resultaten van veldexperimenten zowel kwalitatief als kwantitatief kan simuleren. Deze resultaten zijn beschreven in Hoofdstuk 4.

Het model werd gebruikt voor simulatie van de potentiële opbrengst van tarwe in verschillende regio's. De gesimuleerde potentiële tarweopbrengst varieerde tussen de 2,56 en de 8,25 t korrels ha^{-1} afhankelijk van de locatie. In veel districten van de staten Punjab, Uttar Pradesh, Bihar, Assam, Rajasthan en Madhya Pradesh was de potentiële opbrengst 7 t ha^{-1} of meer. De meeste districten in Uttar Pradesh hadden een potentiële opbrengst van 6 tot 6,5 t ha^{-1}. De potentiële opbrengst lag in centraal India en in de staten West Bengal en Madhya Pradesh tussen de 5 en 6 t ha^{-1}. Vervolgens werden de economisch optimale N-giften voor geïrrigeerde systemen voor alle situaties geschat op grond van de huidige prijsverhoudingen van N-meststoffen en graan, natuurlijke bodemvruchtbaarheid, de aangenomen gewasreactie op N-bemesting en kosten zoals transport, oogsthandelingen en marktfactoren. Uit de vergelijking van optimale en werkelijke N-giften bleek dat in het Ludhiana district in de Punjab de werkelijke N-giften hoger zijn dan de optimale terwijl het in andere districten overeen kwam of lager was. De geschatte opbrengsten die overeenkwamen met de op winstmaximalisatie gebaseerde N-gift waren over het algemeen 200 tot 500 kg ha^{-1} lager dan de potentiële opbrengst. Het kleine verschil tussen potentiële en economisch optimale opbrengstniveaus was het gevolg van verstoorde, maar gunstige, prijsverhoudingen op het

moment van de studie. In regenafhankelijke systemen waar irrigatie moeilijk is of erg duur, zouden economisch optimale opbrengsten lager zijn dan de nu gepresenteerde waarden.
Op de meeste locaties is er een groot verschil tussen de actuele en de potentiële opbrengst. In de geïrrigeerde gebieden van Noordwest India, de belangrijkste graanproducerende regio, is het verschil 1 tot 2 t ha^{-1}. In de rest van de gebieden is het verschil meer dan 2 t ha^{-1}. Ongeveer 35 - 50% van het verschil kon worden toegeschreven aan een te late zaaidatum. Factoren zoals beperkte hoeveelheden en niet tijdig beschikbare meststoffen, gangbare gewassystemen en slechte beschikbaarheid van krediet en andere diensten zijn de andere belangrijkste oorzaken van het verschil tussen potentiële en actuele opbrengsten. Deze resultaten zijn beschreven in Hoofdstuk 5.

In Hoofdstuk 6 zijn de effecten van klimaatsverandering op de productiviteit van tarwe in India beschreven. Een toename van de temperatuur met 1 °C gedurende het gehele seizoen heeft nauwelijks effect. Slechts een kleine toename van de productiviteit werd gesimuleerd voor geïrrigeerde en regenafhankelijke systemen in Noord India. Een temperatuurstoename van 2 °C zal de potentiële opbrengsten reduceren. Maar, het effect op de opbrengsten in geïrrigeerde gebieden in Noord India zou klein zijn. De evaporatie zal significant verminderen bij een veranderd klimaat. Het effect van klimaatsverandering zal relatief het sterkst zijn in Centraal India waar de potentiële opbrengst al laag is. De gewasreactie op klimaatsverandering is het gevolg van het effect van temperatuur op de groeiduur van het gewas.
In Zuidoost-Azië wordt momenteel geen tarwe geproduceerd. De volledige vraag naar tarwe wordt gedekt door tegen hoge kosten graan te importeren. De regeringen in deze landen willen graag de mogelijkheden verkennen om tarwe in die regio te verbouwen. Traditionele agronomische experimenten duren vele jaren. Daarom is een eenvoudig gewasgroeimodel gebruikt om de potentiële opbrengst van tarwe voor verschillende regio's van Zuidoost-Azië te berekenen (Hoofdstuk 7). De locaties waar de regenval toereikend is voor de waterbehoefte van het gewas werden eerst geïdentificeerd. Vervolgens werd vastgesteld of tarwe past binnen de op rijst gebaseerde gewassystemen.
Het verhogen van de potentiële opbrengst is een van de belangrijkste doelstellingen van veredelingsprogramma's. Dat is erg belangrijk voor verschillende Aziatische regio's omdat er slechts een klein verschil is tussen potentiële en actuele opbrengsten in de geïrrigeerde regio's. Gewasgroeisimulatiemodellen integreren gedetailleerde fysiologische en morfologische kennis om opbrengstvorming in milieus die verschillen in fysische, biologische en agronomische factoren te verklaren. Deze modellen hebben daardoor de mogelijkheid om de beste combinatie van planteigenschappen vast te stellen die nodig is voor het verhogen van de potentiële opbrengst. De modellen kunnen ook worden toegepast om verschillende hypotheses te onderzoeken en om ideotypen te ontwikkelen waarmee de doelstellingen voor de veredeling kunnen worden bepaald. Gevoeligheidsanalyse voor de parameters is vergelijkbaar met het creëren van genetische isolijnen omdat slechts één eigenschap wordt veranderd.
Diverse experimenten worden jaarlijks in India op vele locaties uitgevoerd met rijst- en tarwevariëteiten met een verschillende groeiduur. WTGROWS werd gebruikt om de optimale groeiduur en het optimale bloeitijdstip voor geïrrigeerde tarwe in sommige typische rijst-tarwe systemen in India vast te stellen (Hoofdstuk 8). De reactie werd geanalyseerd van zes

vroege, gemiddelde en late variëteiten, die verschillen in de temperatuursombehoefte voor de fase van opkomst tot bloei. De waarde waarbij de opbrengst tussen de 90 en 100% van het maximum was, werd als optimale groeiduur vastgesteld. De resultaten lieten zien dat voor normale zaaidata (15 November) vroege variëteiten het meest geschikt zijn voor de Punjab, variëteiten met een gemiddelde groeiduur het meest geschikt zijn voor de omgeving van New Delhi en Uttar Pradesh en late variëteiten het best zijn in West Bengalen en Bihar. Klimatologische verschillen leidden tot variatie in de optimale groeiduur.
Een methodologisch raamwerk voor het gebruik van gewasgroeimodellen voor het ontwerpen en evalueren van planttypen werd ontwikkeld (Hoofdstukken 9 en 10). Deze benadering vereist het gebruik van modellen die goed zijn geëvalueerd in de specifieke milieus. De kritische gewasparameters werden vastgesteld met behulp van gevoeligheidsanalyse. De benadering is geïllustreerd voor rijst in Hoofdstuk 9. Modelanalyse liet zien dat geen enkele individuele eigenschap de potentiële opbrengst sterk kan verhogen. Een gecombineerde toename van 'sink'sterkte, en vooral, korrelvullingsperiode zijn belangrijk voor het verhogen van de potentiële opbrengst. De resultaten lieten ook zien dat het relatieve belang van de verschillende eigenschappen verschilde per seizoen. Door 30 jaar historische weersgegevens te gebruiken voor een specifieke locatie was het mogelijk de kans op hogere opbrengsten in variabele tropische milieus te simuleren en alternatieve opties voor een vergelijkbare opbrengstverhoging te verkennen.

De Monte Carlo simulatiebenadering werd gebruikt om hypothetische variëteiten met variatie in één of meerdere eigenschappen te evalueren. In deze benadering worden verschillende planteigenschappen verondersteld stochastisch verdeeld te zijn. Veel verschillende variëteiten kunnen worden samengesteld die elk een unieke eigenschappencombinatie hebben. Deze variëteiten bootsen nakomelingen na van een kruising voor verschillende eigenschappen. De opbrengst van deze hypothetische variëteiten werd gesimuleerd voor de verschillende relevante productiesituaties. De resultaten geven dan aan wat het belang is van de verschillende eigenschappen in de verschillende situaties en geven tevens aan wat de doelstellingen m.b.t. verschillende eigenschappen zijn voor de veredeling. Deze analyse liet zien dat de testvariëteit IR72 (rijst) een hoge potentiële opbrengst heeft die alleen gerealiseerd kan worden met een verbeterd N-management (Hoofdstuk 10). Geen enkele individuele eigenschap of combinatie van eigenschappen leidde tot een opbrengstverhoging van meer dan 5% op het management niveau dat wordt toegepast door de veredelaars. De volgende conclusie van deze studie had belangrijke gevolgen voor de veredelingsmethodologie. Op het managementniveau dat momenteel wordt toegepast door de veredelaars is het niet mogelijk variëteiten met een verhoogde potentiële opbrengst te vinden, zelfs als het genetisch materiaal eigenschappen voor een verhoogde potentiële opbrengst heeft. Deze eigenschappen hebben een betere N-voorziening nodig om tot expressie te komen. In dergelijke productiesituaties is een verhoogde 'sink'capaciteit nodig die verkregen kan worden door de lengte van de aarvormingsperiode te verlengen, door de factor die de toename van de pakjes aangeeft te verhogen of door het maximale korrelgewicht te verhogen. Variabiliteit in alle drie de factoren is aangetoond. Naast de verhoogde 'sink'capaciteit is het noodzakelijk dat het blad N-gehalte hoog blijft en de korrelvullingsfase wordt verlengd.

Experimenten om rassen te testen in veel verschillende productiesituaties zijn duur en moeten gedurende verschillende groeiseizoenen en op verschillende locaties worden uitgevoerd om inzicht te krijgen in genotype × milieu (G × E) interacties. Ondanks het feit dat intensieve evaluatieprogramma's met nieuwe genotypes worden uitgevoerd is het niet mogelijk om de volledige range van milieus te bestrijken. Gewasgroeimodellen beschrijven relatieve trends als gevolg van milieuvariatie goed. Dat komt zeer goed van pas bij de selectie van cultivars waar de relatieve korrelopbrengst wordt toegepast als criterium in plaats van de absolute opbrengst. In Hoofdstuk 10 is een modelraamwerk beschreven om gewasgroeimodellen en statistische technieken in samenhang toe te passen om de efficiëntie van experimenten, waarin genotypes in verschillende milieus worden getest, te verbeteren. Gedetailleerde experimenten op verschillende locaties, waar tevens gedetailleerde metingen zijn verricht om modelparameters te schatten, zijn niet beschikbaar. Daarom werd de korrelopbrengst van 26 cultivars in geïrrigeerde productiesituaties gesimuleerd met het model ORYZA1 voor 10 locaties gedurende meerdere jaren. De genotypen werden gecreëerd door *random* combinaties te gebruiken van 8 modelparameters die binnen een kleine marge werden gevarieerd om de variatie die in een experiment op verschillende locaties in verschillende jaren verwacht zou kunnen worden te simuleren. Milieu-effecten en G × E interacties hadden dezelfde orde van grootte als de interacties die waargenomen zijn in geïrrigeerde INGER experimenten. De simulaties en de AMMI analyse resultaten gaven aan dat het model realistische G × E interacties genereert die geanalyseerd en geschat kunnen worden met behulp van statistische technieken. Een vervolgstap is de modelmatige en statistische analyse van experimentele gegevens van verschillende genotypen in diverse milieus.

In Hoofdstuk 11 worden de resultaten van de voorgaande hoofdstukken geïntegreerd besproken in relatie tot de doelstellingen van dit proefschrift. Deze algemene discussie gaat in op de beperkingen van de studie en uitdagingen voor toekomstig onderzoek.

Curriculum vitae

Pramod Kumar Aggarwal born in 1954 in New Delhi, India, obtained his M.Sc. degree in Botany in 1975 from University of Delhi, New Delhi. In 1976, he joined Indian Agricultural Research Institute (IARI), New Delhi as Scientist (Crop Physiology). His main research here was on drought resistance mechanisms in wheat. The University of Indore, India, awarded him a Ph.D. degree in Life Sciences in 1983 for his work on stress physiology of wheat. Indian National Science Academy recognized him with a *Young Scientist* award in the same year for this research. This research also earned him *RD Asana Medal* of the Indian Council of Agricultural Research, named after the famous Indian Plant Physiologist.

In 1985, he joined International Rice Research Institute (IRRI), Philippines for two years as a Visiting Research Fellow. Here, he worked on sustainability of rice based cropping systems as well as on crop modelling. He returned to IARI in 1987 to continue his work on crop modelling and its application to quantify yield potential of wheat in India. In 1994, he joined IRRI as a Visiting Scientist to co-ordinate the Potential production theme of the Simulation and Systems Analysis in Rice Production (SARP) project. During this assignment, besides assisting network scientists in crop modelling, he did research on use of crop models in plant breeding. In 1996, he returned to IARI and started working on modelling rice-wheat systems. His current interests are in the applications of systems simulation for land use planning at different scales, yield forecasting and crop improvement.

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