Crop response to water under irrigated conditions

P. J. SLABBERS
International Institute for Land Reclamation and Improvement

Introduction

Before the dawn of recorded history, farmers had recognized that good water management meant higher crop yields. Early civilizations were founded on the stable food production systems that farmers had created through irrigation or other practices like controlled flooding and water conservation.

Demographers tell us that the world's population will be doubled by the year 2000. Mankind is thus facing an enormous challenge: to feed those extra mouths, it must rapidly and vastly increase its food production. Certainly, much of this challenge will be met by improving rain-fed farming systems, which account for 84 per cent of the world's total cultivated area, but irrigated agriculture will also have a great role to play.

Most of the basic and applied research in the world is conducted in the technologically advanced countries, whereas most of the world's irrigated areas are located in developing countries. As it is precisely in the latter countries that the demand for greater food production will be the most pressing, it is vital that we consider the advances made in the western world and examine the extent to which they have been, and can be, transferred to the developing countries.

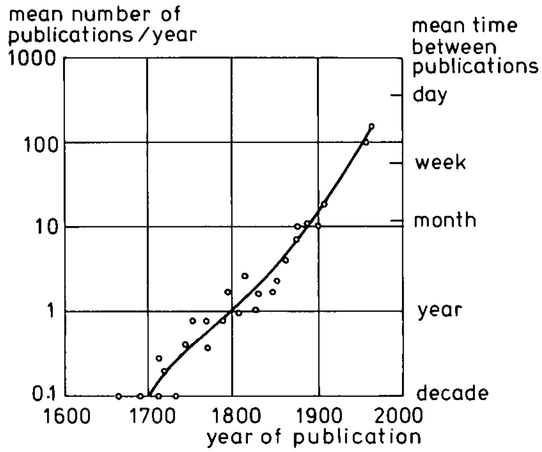
In the search for ways of raising food production under irrigation, a central theme is the study of soil-water-plant relations. These relations are the underlying principles of the effect that water has on crop yield. Many sciences are involved in working towards a better understanding of them. Indeed, research in such fields as soil physics, meteorology, and plant physiology has contributed substantially to better water management systems and to more stable cropping systems. Traditionally, most of the research into the relationships of soil, water, and plant has been directed towards cash crops such as cotton, hybrid maize, and sorghum. And much of that research has concentrated on optimizing the factor 'water', assuming other production factors to be not limiting for crop production. But to what extent are the advances made in such research of practical value under conditions where these other factors are indeed limiting? Let us examine the issue.

A crop's response to water is closely related to the amount of water used by the crop. We shall therefore first turn our attention to the subject of crop water use and discuss the progress made in this field. We shall then turn to our main subject, i.e. the effect of water on crop yield, and follow it with examples in practice. Finally, we shall attempt to predict the developments that may take place in times to come.

Crop water use

At the beginning of this century, researchers were

Figure 1.
Growth of meteorological literature on crop water use since 1670. Mean annual number of publications per decade (STANHILL 1973a).



showing particular interest in the relation between the water use of a crop (transpiration) and the crop's dry matter yield, expressed as transpiration or water use efficiency (kg.kg.$^{-1}$). Many attempts were made to determine the ratio between the two. De WIT (1958) re-analyzed some of these studies and explained much of the observed variations in this ratio.
In the last decades, the interest being taken in crop water use has grown enormously. STANHILL (1973a) estimated that literature on the subject exceeded 18,000 items. Of this total, about one quarter is meteorological literature, i.e. studies on the relationship between weather factors and crop water use. Figure 1 illustrates the prodigious growth of this literature since 1670. Stanhill also estimated that during the mid-1960s the annual cost of studies on crop water use was of the order of 10 million dollars. His figures refer only to the research reported in international literature. They thus leave out of account the research being conducted in developing countries, because few of these reports are easily accessible.
So 18,000 items of literature is probably a very conservative estimate. And if we consider the highly sophisticated tools now being used in crop water research, we can probably conclude that the current annual costs are several times Stanhill's estimate.
A large majority of the work reported concerns methods with which to estimate 'potential evapotranspiration', i.e. the maximum amount of water a crop can transpire. Almost all these methods use one or more meteorological parameters, and most of them are empirical (e.g. Blaney-Criddle, Thornthwaite, Turc, and pan evaporation methods). As they need to be calibrated locally, they have only limited applicability.
The main difficulty in using the above methods is the need for crop coefficients with which to convert an estimate of open water evaporation to potential evapotranspiration of a given crop.
Many field trials have been, and are being, conducted to measure the potential evapotranspiration and then to relate the measured values to meteorological parameters or functions thereof. Publications by JENSEN (1973) and DOORENBOS and PRUITT (1977) compile experiences from many of these trials and present modifications of some of the more widely used methods, including recommended crop factors for each method.
For the accuracy required in feasibility studies and for project design and operation, the current methods of estimating potential evapotranspiration would seem to be adequate, although for day-to-day irrigation scheduling, local calibration is still required.
From a scientific viewpoint, only two important developments have contributed to a better knowledge of evaporation theory: the work of PENMAN (1948) on the combined heat-balance/mass-transfer equation and the eddy correlation method of SWINBANK (1951).
Typical of all that work on crop water use is its orientation towards maximum crop yields and its concentration on cash crops. The underlying philosophy was that one should aim at maximum crop yields per unit of land. Over the last ten years, a shift away from that philosophy has become apparent. The realization that supplies of good quality water are limited and that these supplies are also being competed for by industry and domestic users has been calling for a more efficient use of irrigation water. Considerations of energy costs and capital investments are also involved. As a result, 'deficit irrigation' has come to be accepted in many circumstances. It has been found that optimum crop yields can still be obtained even though the crop 'suffers' from water shortages during certain stages of its growth. Withholding water during these stages obviously decreases the crop water use.
An example of how evapotranspiration drops with longer irrigation intervals is shown in Figure 2. (The crop is cotton on a fine-textured soil in Egypt).
As can be seen, for some time after irrigation the

crop transpires at the maximum rate and then, as the soil dries out, this rate drops. Whether a reduced rate of evapotranspiration is permissible depends on the effect such reduction would have on the crop.
Accompanying the acceptance of deficit irrigation is the growing interest in the development of practical methods of estimating 'actual evapotranspiration', i.e. crop water use under limiting water availability. Important research in this field has been reported by RIJTEMA (1965), MONTEITH (1965), and RIJTEMA and ABOUKHALED (1975). Some of this research takes the form of establishing production functions, i.e. of indicating how crop yield varies with changing water availability; some researchers use models to describe this relationship.
Better instrumentation (thermocouple psychrometer, porometer, neutronmeter, etc.) is enabling more accurate measurements of the soil-water-plant status and its interactions, which can then be described mathematically and generalized for broader application. A new avenue is being opened by the use of remote sensing techniques. With 'traditional' instrumentation, it had previously been difficult to determine surface temperatures, but remote sensing techniques are now overcoming this problem.

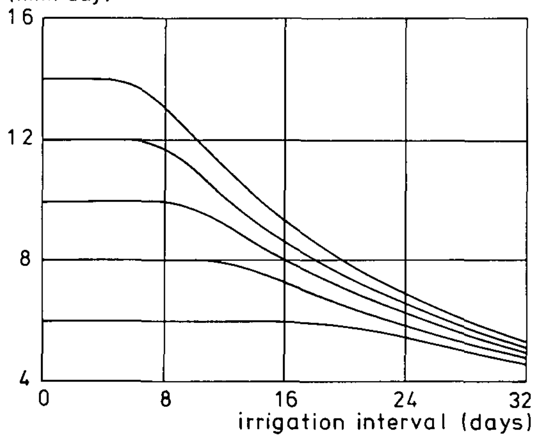


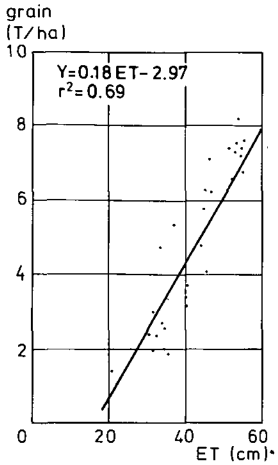
Figure 2.
Mean actual ET cotton over the irrigation interval for different durations of irrigation interval and for different ET cotton levels (RIJTEMA and ABOUKHALED 1975).

Modelling the effect of water on crop yield

With the 'rediscovered' importance of the effect of water availability on crop yield and the great complexity of the relation between the two, sophisticated models have been developed, ranging from statistical models to crop growth simulation models. But, as in many other sciences, people are now returning to more simplified methods. This is especially true for applications in developing countries where the detailed data for complicated models are lacking. In the meantime, however, the use of complicated models has contributed much to the improvement of simpler models.
In discussing the different approaches followed in assessing relationships between crop water use and crop yield, it is convenient to divide them into three groups:
- simplified agroclimatic indices
- crop-weather models, and
- simplified crop-water-use/yield models

Simplified agroclimatic indices

It has always been difficult to describe exactly how water affects crop yield. Research has therefore been seeking one factor (or a combination of a few factors) that has some relationship with water availability. Such a factor is then called an index. The most simple index of water availability would be seasonal rainfall (or rainfall plus water supplied under irrigation). However, the relation between rainfall and crop yield varies from year to year and depends on the distribution over the season. Another index therefore had to be sought. A convenient one, and one often used, is evapotranspiration (the amount of water used by a crop).
Evapotranspiration provides an agroclimatic index which, apart from integrating soil characteristics as is done when soil water status is used as an index, also includes the effect of plant factors. Evapotranspiration is thus widely used for assessing the effect of water supply on crop growth and yield.
STANHILL (1973b) presented a review of studies and methods in which evapotranspiration, in some form, is used as an index. Some more recent examples are briefly described here.
For a number of crops and conditions a close linear relationship has been found between actual evapotranspiration (ET) and crop yield. An example, adapted from HANKS et al. (1978) is shown in Figures 3 and 4 for corn grain yield and corn dry matter yield, where r = correlation coefficient.
There is increasing evidence, both theoretical and practical, that such linear relationships need to be



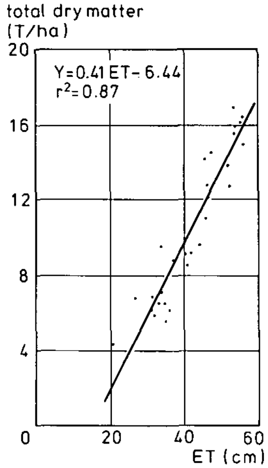


Figure 3.
Corn grain yield in 1975 (15.5% moisture) as related to evapotranspiration at Logan.

Figure 4.
Corn total dry matter yields in 1975 as related to evapotranspiration at Logan.

modified to allow transfer to climatologically different areas, and also that growth stages in crop development need to be taken into account when relating evapotranspiration to yield.
A simple but illustrative example of how the timing of irrigation and the quantity of water applied affects crop yield is shown in Figure 5.
The data originate from an irrigated wheat trial at the Texas Agricultural Experiment Station. The only variant between treatments of one to four irrigations of uniform depth was their application at different stages of growth. All these stages fall within a period in which wheat is known to be critical to available water. It is seen that at the same level of crop water use the yield may vary as much as 30 per cent, depending on the timing of water application.
Studies in Canada, U.S.A., and Australia in the late sixties showed the usefulness of using the ratio of actual to potential evapotranspiration at defined growth stages as an index of crop yield. A nice example of this approach is given by NIX and FITZPATRICK (1969), who obtained even better results by using a 'stress index' consisting of the estimated available water (mm) at the beginning of the critical flowering stage divided by the mean potential evapotranspiration rate during the critical period. (mm.week^{-1}). Figure 6 shows such a relationship.
A comparable approach was followed by Hagan and associates (see e.g. STEWART et al. 1973). Some of their results are shown in Figure 7, where variation from year to year is taken into account by using evapotranspiration and yield *reductions*.
The effect of growth stages is introduced by breaking the spectrum of results into zones representing different ranges of yield reduction ratios as expressed by the percentage of yield reduction divided by the percentage of ET reduction. Zones are then found to be the result of different evapotranspiration sequences, i.e. the regime of optimum or suboptimum water availability throughout the growing season. These are just a few examples of the numerous approaches to using simple expressions of evapotranspiration as an index of the effect of water supply on crop yield. Such relatively simple agroclimatic indices have proved to be of value provided they are locally calibrated.

Crop-weather models
Crop production is generally determined by the prevailing environmental conditions, i.e. by the existing complex of physical, chemical, and biological factors. Considerable progress has been made in recent years in quantitatively expressing plant performance by a function that integrates the many variables that comprise the environment.
To obtain data suitable for such a function, one of two experimental approaches is usually followed: either experiments are conducted in con-

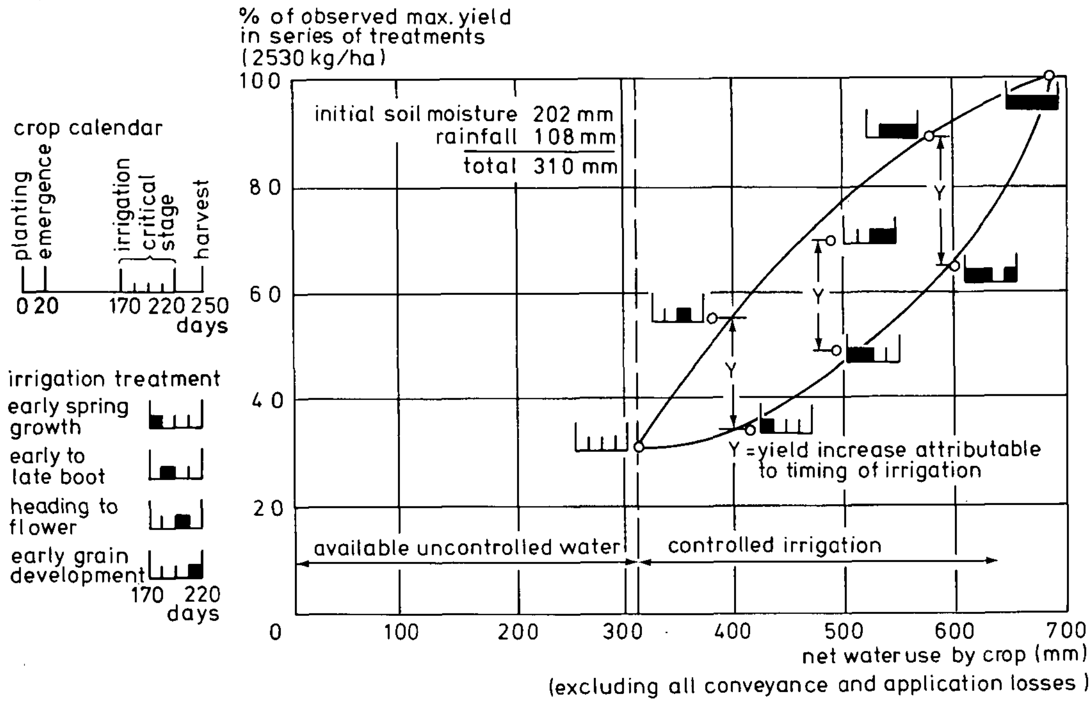


Figure 5.
The influence on wheat yield of amount and timing of irrigation.

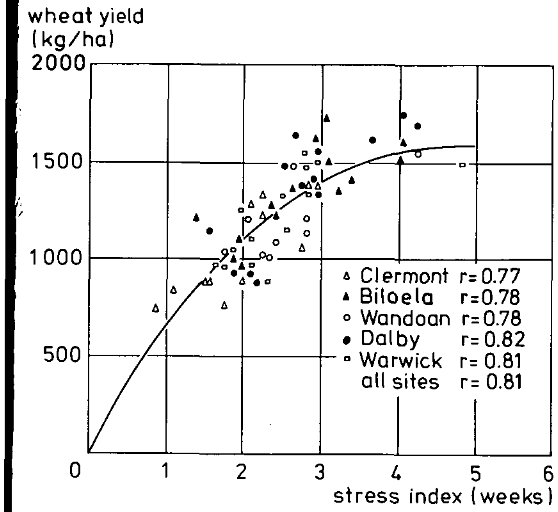


Figure 6.
Relationship between wheat yields and computed stress index at five centres in Queensland between latitudes 22 °S and 20 °S. (NIX and FITZPATRICK 1969).

trolled climates (e.g. glasshouses) where only one or a few elements are controlled according to the experimental plan; or, field experiments are conducted in which, as far as possible, all variables except weather (or water supply) are standardized.
With such limitations, it is obvious that the crop-weather relationships so obtained are difficult to apply under practical conditions where other variables will also affect crop yield.
BAIER (1979), in analyzing current crop-weather models, distinguishes between the following three types:
- crop-growth simulation models
- crop/weather-analysis models, and
- empirical statistical models
In *crop-growth simulation models*, the effect of meteorological variables on such processes as photosynthesis, transpiration, or respiration is simulated by a set of mathematical equations based either on experiments or on available knowledge. These processes are then integrated to simulate crop growth. Examples of large plant growth models are ELCROS, SPAN, and SIMED, known by their abbreviated names.
The *crop/weather-analysis models* use soil moisture, evapotranspiration, or other data derived on a day-to-day basis, and relate these data to factors like crop yield. These models often incorporate a sub-model ('biological clock') to monitor the state of crop development towards maturity. An example is the model presented by BAIER (1973).
The *empirical statistical models* use yield and weather data to arrive at estimates of coefficients by some type of regression technique. Such models do not explain a cause-and-effect relationship, but are useful in relating available yield data to climatic data to evaluate historical, current, and to some extent future crop yield statistics. Examples are the regional yield prediction models for wheat, barley, and oats by WILLIAMS et al. (1975).
These three types of models can all be defined as simplified representations of the complex relations between crop performance and weather; all use established mathematical and/or statistical techniques.

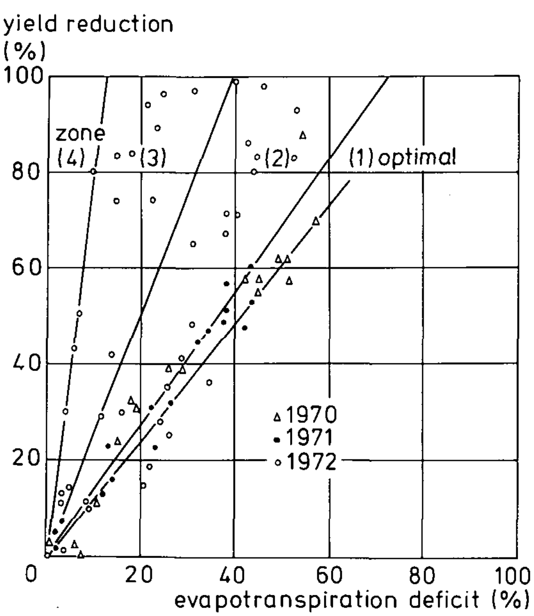
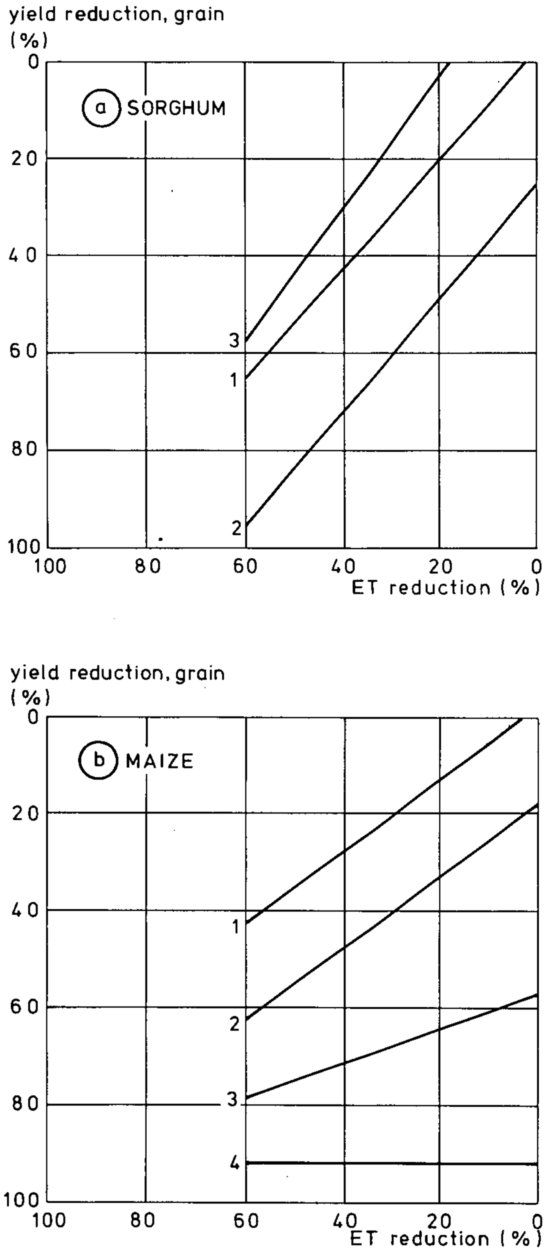


Figure 7.
Division of 3-year corn data into zones to analyse relations between ranges of yield reduction ratios and associated ET deficit sequences (STEWART et al. 1973).

Important breakthroughs in the development of models have been: potential evapotranspiration, heat units and their various modifications, soil moisture budgeting, and similar techniques that require only standard climatological data as input. This applies especially to the crop/weather-analysis models and the empirical statistical models.
With increasing fundamental research, various plant processes like photosynthesis, water flux in plant and soil, translocation, respiration, light interception etc., are now better understood. Thus the scope for integrating the descriptions of such processes into large-scale crop simulation models is expanding.

Simplified models

Apart from the simplified *indices* described earlier, simplified *models* are gaining rapidly in popularity. Their development has been possible by the advances made in process models. These simple models generally concentrate on only one practical variable and usually employ longer periods of time than those used in larger models. Examples are the model of FEDDES et al (1979), which concentrates on the effect of soil-physical aspects of water use and crop yield, and that of SLABBERS et al. (1979), which concentrates on the effect of growth stages on water-use/crop-yield relationships.
Several such models are based on the early work



of de WIT (1958) and on that of BIERHUIZEN and SLATYER (1965) from which we know that water use and productivity are dependent on the supply of radiant energy and that both are influenced by plant and environmental factors that control gaseous transfer between plants and the atmosphere. By expressing these processes in mathematical equations, a correlation can be found between water use and productivity.
An important contribution to this work was made by de WIT (1965) with his computation of photosynthesis of a standard crop under standardized conditions. This computation can be used to correlate water use and productivity data from climatologically different areas.
An application of such a model is shown in Figure 8.
To determine the relative reduction in yield, the potential grain production was calculated by a linear model based on standard meteorological and agronomic data. (For details, see SLABBERS et al, 1979). The relations 1 to 4 refer to different ET deficit sequences throughout the growing season. Calibration and testing was done against data obtained under controlled conditions (experimental stations), with water as the only variable.
Simple presentations of crop response to water are given by DOORENBOS and KASSAM (1979). Further verification of such simple relationships is still required.

Figure 8.
Relation between reduction in evapotranspiration and reduction in grain yield for sorghums (A) (4 locations, 6 seasons) and for maize (B) (3 locations, 5 seasons) for different sequences of ET-deficits.

Applications in water management

In the U.S.A., where research has produced much accurate information on crop water use, models are being increasingly used to improve water management practices. Results from lysimeter studies, for instance, have been incorporated into computer models to estimate crop water use under prevailing and predicted weather conditions. These estimates are then fed into irrigation scheduling models. Commercial scheduling services and the Bureau of Reclamation employ scheduling procedures that use weather factors to predict when and how much to irrigate, combined with field measurements (gypsum blocks, gravimetric sampling or neutron meters) to adjust for water application and rainfall inaccuracies. Such services were used for the irrigation of more than 300,000 acres in 1976 (SPLINTER 1976).
There is a growing tendency to incorporate plant growth (sub-)models in irrigation scheduling models.
For developing countries, such refined techniques of irrigation scheduling are still a utopia. There, irrigation projects are still being designed as they were several decades ago; their layout does not permit variable irrigation scheduling. Even so, there are signs that also in the developing countries work is underway to find practical production functions for irrigated crops. An example from the Philippines is reported by ROSE-

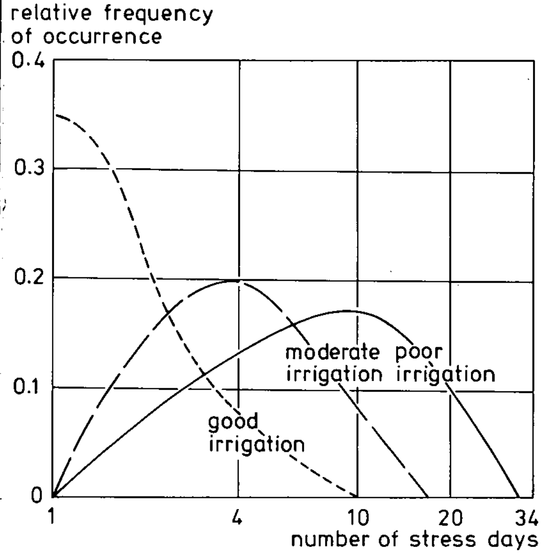


Figure 9.
Relative frequency distribution of days with serious water shortage for different standards of irrigation, dry season (ROSEGRANT 1977).

GRANT (1977) and cited by LUNING (1978) in which a production function for modern rice varieties was estimated from a combination of data from research and from small rice farms in Central Luzon. Separate functions were estimated for the wet and dry seasons and for irrigated and rainfed crops. This allows crop yields to be expressed as a function of such factors as initial yield level, nitrogen fertilization, number of days with serious moisture stress, solar radiation, insect damage, and typhoon damage. Used in establishing the production function were time series of meteorological data, data from representative irrigation systems, interviews with farmers on insect and typhoon damage, and data from research stations (on nitrogen response). Frequency distributions were established for independent variables (sunshine, insect and typhoon damage, moisture stress duration) under varying standards of water management. An illustration of the moisture stress duration variable is given in Figure 9.
Figure 10 illustrates the use of such frequency distributions in establishing the relation between crop yield and nitrogen levels.
Like all the previously cited examples, the Philippine study concerns factors that are environment-determined. None of the examples considers the farmers's attitude towards risk and uncertainty. LUNING (1978) describes such methodology as assessments of 'objective probability' as against assessments of 'subjective probability', which are based on the farmer's decision model. As yet, we know very little about how the farmer, when confronted with a number of alternatives, arrives at his final decision. Slowly we are beginning to grasp the risks he is running in his environment, but we are not able to predict how he will react.

Avenues for the future

Whilst it is obvious that much progress has been made in understanding the soil-water-plant continuum, much still remains to be done before we arrive at the future state as envisaged by SPLINTER (1976):
'We can look for computer-assisted farm management practices to include irrigation, application of fertilizer, application strategies for insecticides, herbicides, and fungicides. We can expect electronic monitoring of the water status in fields and the water status of the plant canopy to be fed to a central computer for a decision-making by the individual farmer. We can see an increased level of technology going into the machines and devices for applying irrigation water, for laying out tile fields, and for laying out and designing terraces with greater precision. As our demand for food doubles over the next 25 years, we can expect the pressures to push research and development in the soil and water area to the forefront'.
In the meantime, however, some disquieting observations have been made. GRANT (1979) notes that in parts of the U.S.A. conservation practices are being abandoned. Terracing, wind breaks, contour ploughing are no longer practised because of the use of centre pivot sprinkling equipment and agricultural machinery that requires large fields of certain dimensions.
Farmers' recent inclination towards short-term profits, brought about by market structures and price policies, is also a contributing factor.
For the immediate future, we can expect that major stress will be placed on the conservation of water resources and on low energy bills. At the same time, there will be increased pressure on soil and water research to produce knowledge that will serve an ever more sophisticated agricultural system. In the developed countries, farms

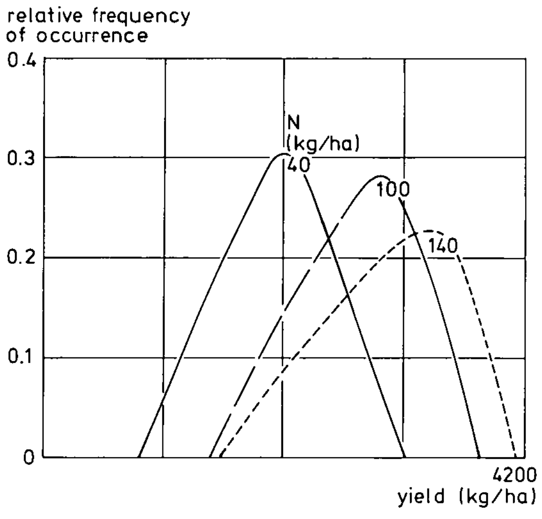


Figure 10.
Crop yield distribution for different N-levels, average standard of irrigation, dry season (ROSEGRANT 1977).

will be operated by university graduates, as agricultural production becomes increasingly industrialized and mechanized as a substitute for labour.

But what will happen in the developing countries? How will they cope with the need for a vast expansion of their food production? What can be done to help?

Efforts are underway to provide developing countries with an early warning system if possible crop failures and resulting food shortages are predicted. In exchange for the supply of meteorological and crop statistical data, these countries obtain predictions of crop yields and crop performances. Inherent to this procedure, as pointed out by many, is the danger that such information may be misused for political purposes. There is a need for some form of built-in protection for the developing countries so that the exercise will serve its original purpose only.

Because of the lack of funds and facilities and the shortage of qualified people, it cannot be expected that developing countries will conduct the intensive research that is being done in the developed countries. Nor is there any need to do so. Much of it would be mere duplication. What is needed is the development of methods that will allow research results, obtained under certain conditions of climate, soils, and crops, to be transferred to other places where basic data on such conditions are scarce.

Although this will be an important step in the right direction, the advances made in the western world can only be of value to the third world if irrigation water can be carefully controlled. As this will require heavy investments in irrigation system design and intensive training activities, it is difficult to be optimistic about the short-term contribution that western research can make to an increased food production in the developing countries. Truly appropriate technologies in this field have yet to be developed.

Although an enormous amount of research is necessary to establish the farmer's dependence on environmental factors, at least the methodologies and techniques to do so are now becoming available. But the practical application of such work to the millions of small farmers in the developing world is limited by a lack of knowledge of the farmer's decision model. Especially in irrigated agriculture, where the farmer is dependent on outside management, much more needs to be known about his attitude towards risk and uncertainty. More knowledge on this subject will lead to socially acceptable improvements in the organization of irrigation projects— improvements that must precede any technological steps towards optimum crop production.

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