韓作誌 27(4)296~313(1982) KJCS 27(4)296~313(1982)

Effects of Climatic Condition on Stability and Efficiency of Crop Production

Robert H. Shaw*

農業 氣象特性과 作物生産의 効率 및 安全性

로버트 쇼*

ABSTRACT

At a time when world population and food supply are in a delicate balance, it is essential that we look at factors to improve this balance. We can alter the environment to better fit the plant's needs, or we can alter the plant to better fit the environment. Improved technology has allowed us to increase the yield level. For moderately detrimental weather events technology has generally decreased the yield variation, yet for major weather disasters the variation has increased. We have raised the upper level, but zero is still the bottom level. As we concentrate the production of particular crops into limited areas where the environment is closest to optimum, we may be increasing the risk of a major weather related disaster. We need to evaluate the degree of variability of different crops, and how weather and technology can interact to affect it.

The natural limits of crop production are imposed by important ecological factors. Production is a function of the climate, the soil, and the crop and all activities related to them. In looking at the environment of a crop we must recognize these are individuals, populations and ecosystems. Under intensive agriculture we try to limit the competition to one desired species.

The environment is made up of a complex of factors; radiation, moisture, temperature and wind, among others. Plant response to the environment is due to the interaction of all of these factors, yet in attempting to understand them we often examine each factor individually. Variation in crop yields is primarily a function of limiting environmental parameters.

Various weather parameters will be discussed, with emphasis placed on how they impact on crop production. Although solar radiation is a driving force in crop production, it often shows little relationship to yield variation. Water may enter into crop production as both a limiting and excessive factor. The effects of moisture deficiency have received much more attention than moisture excess. In many areas of the world, a very significant portion of yield variation is due to variation in the moisture factor.

Temperature imposes limits on where crops can be grown, and the type of crop that can be grown in an area. High temperature effects are often combined with deficient moisture effects. Cool temperatures determine the limits in which crops can be grown. Growing degree units, or heat accumulations, have often been used as a means of explaining many temperature effects. Methods for explaining chilling effects are more limited.

---

* 美國 아이오와 州立大 著名教授.
* Distinguished Professor of Agricultural Meteorology, Iowa State University, Ames, 50011, U. S. A.

A brief discussion on the efficiency of production will conclude the presentation.

INTRODUCTION

The world population and food supply are generally considered to be in a delicate balance at the present time. World population is increasing. Those areas that are self-sufficient in food production must continue to produce for export to areas that are food deficient. Those areas that are not now self-sufficient must take steps to move toward that goal if long-term needs are to be met. Solving agriculture production problems is not a problem for agriculture alone. What can be done has constraints placed on it because of the political-social-economic systems under which each area operates. As agricultural scientists, we must not forget that point, as frustrating as it seems at times.

The required food supply increase can come from 1) increased yields on land presently being cultivated or 2) by bringing new land into cultivation. Estimates indicate that this increased land area could come from the utilization of about one billion hectares of unused tropical, and 0.5 billion hectares of temperate-zone soils, or from increased production on the presently cultivated 1.4 billion hectares of land. Increased production on presently cultivated lands could be accomplished by improvements in technology, and by reduction of climatic-stress restrictions, i.e., expanded irrigation. Use of new lands will be from marginal areas where greater stress problems will be encountered, and will probably introduce greater variability into agricultural production.

In our quest for greater food production and development of agriculture less sensitive to the whims of Mother Nature, there are options available. We can alter the environment to better fit the plant's needs, or we can alter the plant to better fit the environment. Most of the altering that has been done in developed countries has been to utilize a high-energy-input system to produce much higher yields. Energy costs and environmental pollution constraints are reducing the production inputs to agriculture. Fertilizer and chemical costs have risen sharply. Power costs for irrigation have skyrocketed. Some say our yields are near plateauing, or have already reached that point. Additional inputs may not be economically practical. If yields have plateaued, then much of our increase in production must come from bringing new, marginal lands into cultivation.

High levels of management do not necessarily preclude a crop failure. I believe that management has reduced many of the more moderate weather stresses which might occur. For example, in Iowa our combination of hybrids and fertilizer allows our corn plants to root to 5 or 7 feet with the right weather. Years ago corn plants probably rooted to only 3 or 4 feet. This deeper rooting has made more stored, soil moisture available to the plant to carry it over short, dry periods; thereby reducing or eliminating stress due to these short periods. But what happens when the weather becomes extremely dry? In two consecutive years in northwest Iowa, with no irrigation, corn yields ranged from almost 11,000 kg/ha one year to zero the next. In central Iowa in 1977 we had farmers who did not combine their corn; there simply wasn't any corn there to combine. Yet, in that same year, late soybeans under natural weather conditions yielded as much as irrigated soybeans. We had heavy late summer rains, but they were too late to prevent a weather disaster for corn. These instances point out two important features of weather as it affects the variability of agricultural production – the timing of the weather, and the crop being grown. In this case it was 'when the rains occurred' as well as the amount, that was very important. The determinate corn crop had gone beyond it's critical stage and could not recover. The indeterminate soybean crop could recover, and it set on more pods which developed large beans. Weather may affect different crops to greatly different degrees, and different stages of development may be affected by different factors.

YIELD VARIABILITY

What has the combination of changing weather and increased technology done to the yield variation? An analysis made of annual crop-yield variability in the U.S. during a study conducted by the Institute of Crop Ecology and the Kettering Foundation (1976) showed the following.

In the U.S., sorghum production seems the most influenced by weather variations (coefficient of variation); corn was next, followed by wheat and soybeans. Wheat production in Canada was more variable than in the U.S.

Canadian wheat production is concentrated in an area of 24 million acres. Although there may be some tendency for good conditions in one part of their wheat region to compensate for poor conditions in another part, this is much less effective in reducing the variability of annual yields than in the case of the much more extensive, and climatologically heterogeneous, U.S. wheat region of 69 million acres. If the U.S. spring wheat crop is considered by itself, the variability was comparable to that of the Canadian wheat crop. Corn production is also very concentrated, and is more subject to major weather variations, which often occur over limited land areas. In soybeans, we have a crop with an indeterminate growth characteristic, something which makes it less "weather stress" sensitive, grown over a wide geographical area. Variability of different crops is a function of the crop itself, as well as the weather variability over the area in which it is grown. A crop concentrated in a relatively small geographical area may be more likely to have significant weather-induced variations than one grown over very extensive geographical areas. It would seem very logical to grow a crop in an area where the yields are the higest. But by doing this, we could expose ourselves to extreme variability in a year when a weather disaster was centered over this geographical area. By spreading the crop over a large area, the absolute yield could be reduced, yet because only limited parts of the total acreage were 'weather affected', overall variability might be reduced.

Table 1. Measurements of annual crop yield variability*.

Crop species	Period of record	Mean yield	Standard deviation	Coefficient of variability
	Crop years	Bu/acre	Bu/acre	Percent
U.S. corn	1866-1975	35.6	4.46	12.5
wheat	1866-1975	16.5	1.70	10.3
sorghum	1929-1975	28.5	3.80	13.3
soybeans	1924-1975	20.1	1.50	7.5
Canadian				
barley	1922-1975	27.4	4.50	16.4
wheat	1922-1975	18.6	4.30	23.1

*From McCloud's regression analysis.
(From Institute of Crop Ecology, Charles Kettering Foundation, 1976).

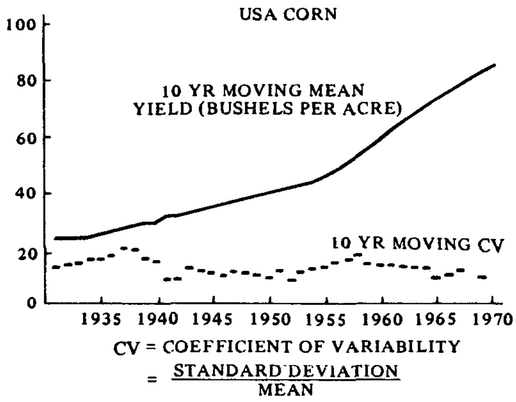

Fig. 1. Coefficient of variability for USA corn yield (From: Institute of Crop Ecology, Charles Kettering Foundation, 1976).

In examining the stability (or variability) of crop production one must also consider what measure of stability is used. Is it the relative variation, or the absolute variation? In Table 1, the standard deviation for sorghum is less than for corn, but the coefficient of variability (a function of the mean yield) is higher. From Figure 1, it can be seen that the average USA corn yield has increased over time. As shown by the *coefficient* of variation, the moving average of the variability shows some high periods and some low periods, with the recent period being relatively low. The variability of yields fluctuates over time.

Some studies indicate that yield variation has decreased with increasing technology. The measure of variation used may almost force that to be true if the coefficient of variability is used. It is probably true that with higher technology we have eliminated, or reduced, the effect of moderately detrimental weather. For most years this would reduce the variation. However, in terms of absolute deviations there is still the potential for greater than ever deviations. We have raised the upper boundary by increasing the average yield level, but have not changed the lower limit – a weather disaster can still result in a zero yield under unusal weather conditions.

In the Institute of Ecology study, yields were calculated for different crops, using the actual weather data for each year, but assuming all years had 1973 technology, i.e., the weather variation is being estimated in terms of the crop yield. Certain weather scenario years were selected for the study.

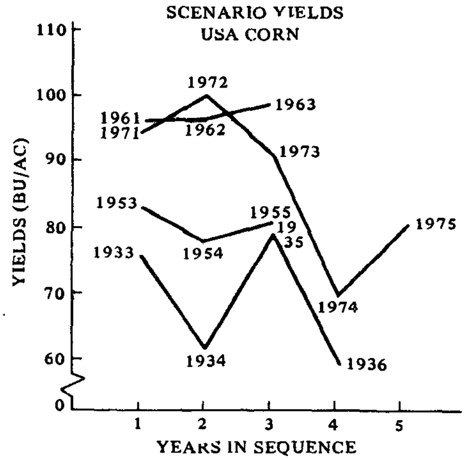

Fig. 2. Scenarios for U.S. corn yields, assuming 1973 technology for all years. (From Institute of Crop Ecology, Charles Kettering Foundation, 1976).

In some scenarios (Figure 2), the yields of all years within that scenario were higher than any year in another scenario, i.e., 1961, 1962, 1963 versus 1953, 1954, 1955. All years in the 1933-36 period had relatively low yields. The 1971-75 period had individual years ranging from among the highest to the lowest. This is the effect that climate can have on production stability: consecutive years may be very uniform, very variable, or the periods may have generally high, low or widely fluctuating yields. In general, the more limited the area where a crop is grown, the more likely it is to see the kinds of variations shown in Figure 2. We should not assume that high periods of variability are due to abnormal periods of weather, and low periods due to normal weather. They may all represent the normal pattern.

DEFINING THE ENVIRONMENT

Although agricultural meteorologists recognize that the atmospheric environment is a very important factor in plant production, we must also recognize that the climate, soil, and plant factors are all important and all interact together. Indirectly climate also has great impact on the other factors. If we consider fertility, plant pathology, entomology, etc., as relating to the soil or plant, we could call this our plant-production triangle. In order to understand each factor, we may examine and study each factor separately, but to evaluate the end result on crop production we must remember they all interact together.

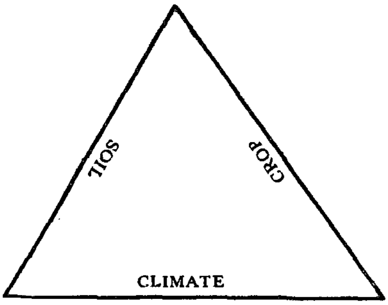

Fig. 3. The production triangle.

The natural limits of crop production are imposed by the important ecological factors, of which climate is a primary one. Some plants can grow only in warm climates because of an exacting temperature requirement. Others may grow only where it is very wet, because of an exacting water requirement. Many plants will grow under a wide range of climatic conditions, and many of our crop plants fall in this category. Wide genetic diversity must be a significant factor in this adaptability, but the range of genetic diversity may vary widely for different crop species, and is an important factor in how plants respond to the environment.

The environment of a plant has been defined as a sum of all the external forces and substances affecting growth, structure, and reproduction. The environment is dynamic, not static and is constantly changing. This means that plant environment relationships are also changing.

There are three levels of integration of the environment:

a) The individual
b) The population
c) The ecosystem.

We need to recognize this is defining the environment.

The effects of climate on an individual, without competition from other plants, may differ significantly from that of a population. A study of the individual may provide the researcher with essential, basic information on plant response, but the response must be interpreted very carefully when applied to a population. A population has genetic diversity, but this may be small (i.e., an inbred variety of corn), or it may be quite large (i.e., an open pollinated variety). Under intensive agriculture, only limited diversity may be present in a local area, and an untimely weather event can be disastrous. Individuals and populations do not live alone, but survive in association with other plants. Intensive agriculture tends to limit this association in the ecosystem by management practice (cultivation, chemical weed control, etc.) so that competition is only between plants of one desired species. We are thus primarily concerned with defining the environment for a population.

Billings (1969) has given three environmental principles that seem most important in governing organism-environment relationships.

a) Principle of Limiting Factors

Von Liebig found that the yield of a crop could be increased only by supplying the crop more of the nutrient present in the least amount. Now that we have high potential levels of production, the environment may more often become a limiting factor. In areas where a selected weather parameter is near its optimum value, small fluctuations in that parameter may show little or no effect on yield. In a correlation type study, these areas may show low correlation with yield. In areas where a parameter is marginal, yield responses may be significant with relatively small changes in the parameter, and correlation studies may show a high correlation with yield. It is not a simple matter to sort out the limiting factor when both technology and weather are involved and both are changing. Present corn yields in the Corn Belt are at a high level. Arguments exist as to how much of this high level is due to technology and how much is due to good weather. Our problem is in quantitatively defining the effects of each. In Figure 4, the relationship between time and an estimate of corn yield is

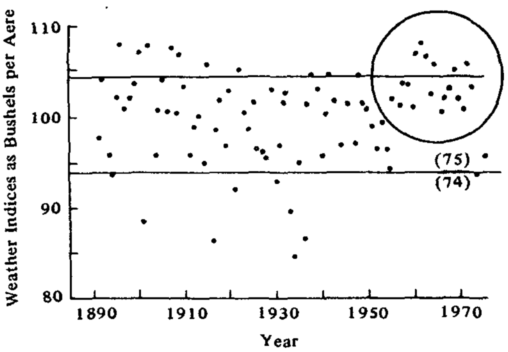

Fig. 4. Simulated 5-state weighted average corn yields using 1973 technology and harvested acreage: Ohio, Indiana, Illinois, Iowa, Missouri. (From: National Research Council, 1976).

shown. The corn yield estimate was computed using the weather data for each year, but a 1973 level of technology for all years. The answer is a type of weather index. With this, and other information, I believe we can conclusively show that we had a series of unprecedented weather in the Corn Belt during the circled years; variability was low. This good weather allowed high technology to assert itself. But in '74 and '75, although technology has reduced the effect of moderately detrimental weather, it did not eliminate the severe weather effects. Variability increased. We need to describe the environment in terms that will explain all of this. We should also recognize that weather may, at times, be the limiting factor, but at other times other factors are *dominant.*

b) Principle of Total Environment

The effects of individual factors, such as temperature, light, or moisture, can be studied under controlled conditions, but it must be recognized that the effects may not always be typical of those produced in nature where all the environmental factors interact. The environment acts as an entity, that is all factors interact with each other. Radiation and temperature are related, as are moisture and temperature, etc. What happens if we change some of these interactions?

c) Principle of Trigger Factors

The removal of a limiting factor may create a chain reaction in the production system. Under managed crop systems this trigger factor may only occasionally be present, i.e. hybrid corn or sorghum, cheap nitrogen fertilizer, or irrigation. When one of these happens we often have to completely reevaluate the relationships. History is no longer a true predictor. With major changes in technology we may also have major changes in the plant environment interaction.

WEATHER PARAMETERS

Radiation

Solar radiation is the driving force of crop production, yet solar radiation data are collected at relatively few sites. Experiments where radiation is changed over wide levels (particularly at low levels) show a high correlation with plant responses like photosynthesis. Different species exhibit different light responses for individual sunlit leaves versus those *in the population.* There are also varietal differences in light penetration in a vertical leaf canopy compared to a horizontal leaf canopy. Only in relatively cloudy areas are radiation effects often significant. Radiation may well be a more constant climate parameter than temperature and precipitation, and not have as *significant an impact* on yield variation.

Water, or the Moisture Factor

Under natural conditions, moisture is one of the most *significant factors* in crop production and worldwide may affect variability more than any other factor. Abundant moisture allows for a wide choice of crops, but where moisture is deficient, only limited choices are available. Moisture has both a supply and a demand side. The adequacy of the moisture is the result of the balance between these factors.

Precipitation is extremely variable and is the main source for water unless irrigation is practiced. I would briefly like to mention one other supply—dew. In total it adds little to the system, but is significant in providing a film of moisture for pathogens. It is not routinely measured, but from the standpoint of plant disease development, probably should be.

Denmead and Shaw (1962) studied the water balance in a field experiment using 25-gallon containers. They found that the soil moisture-transpiration relationship changed for different levels of *atmospheric demand* (Figure 5). At *high demand* levels, the PET rate (the maximum point of the curve) could be maintained only at high levels of soil moisture. With a more moderate demand, the maximum rate (which is lower than for a high demand day) could be maintained over a large range of soil moisture, although for a very low demand day, the rate could be maintained over almost the

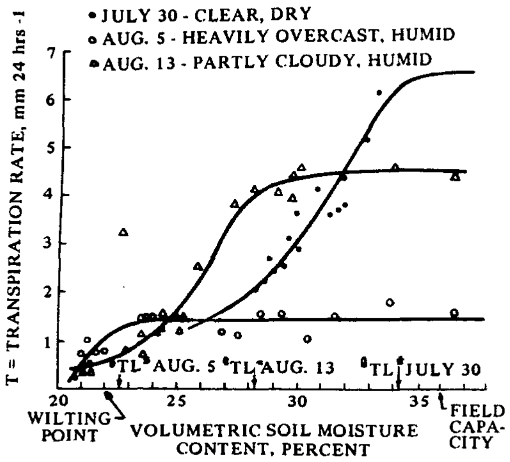

Fig. 5. Actual transpiration rate as a function of soil water content for Colo silty clay loam. θ_{TL} is soil moisture at which turgor was estimated to be lost. (From: Denmead and Shaw, 1962).

entire range from field capacity to the wilting point. The moisture content at which stress developed depended upon the balance between the supply and the atmospheric demand. Besides varying for different demand conditions, it would also vary some for different soil types. Using the principles just explained, we have developed procedures for predicting soil moisture, and a stress index for corn.

An understanding of the relationship between the plant-water status and various plant processes is needed to explain the moisture response of a plant. Boyer (1970) examined the relationships between leaf-water potential, leaf enlargement, and metabolic rates in corn, soybean, and sunflower (Figure 6). Enlargement was very sensitive to declining leaf water potential for all three species. Major changes occurred within a 2- to 3-bar interval, with strongly inhibited rates at -4 to -5 bars. Although rapid leaf enlargement was uniformly sensitive to low, leaf-water potentials in the three species, there were differences when growth rates were low. At leaf-water potentials below -4 bars, enlargement was completely suppressed in sunflower, but continued at low rates in corn and soybeans. The large inhibition in sunflower at such potentials may result in little leaf growth during the day, even in a well-watered soil (Boyer, 1968).

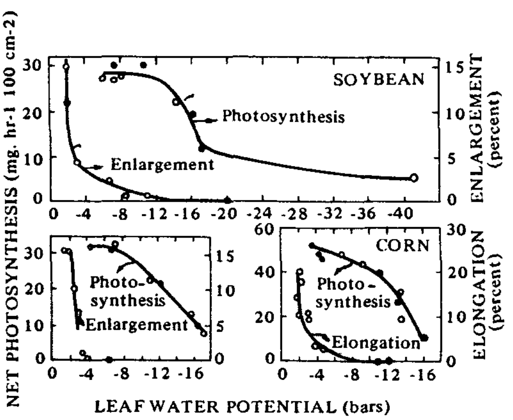

Fig. 6. Rates of leaf enlargement and net photosynthesis in corn, soybean, and sunflower plants at various leaf water potentials. The photosynthesis data were collected from two different plants for each species (o : Plant 1; o : Plant 2). The plants were 45 to 60 cm tall. The growth data for soybean and sunflower represent enlargement of the fourth and sixth leaves from the base of the plant, the leaves having an area of about 20 and 60 cm^2, respectively, at the beginning of the 24-hr growth period. For corn, growth was determined as elongation of the sixth leaf blade. The corn leaf blades were initially 25 to 35 cm long. (From: Boyer, 1970.)

The photosynthetic response to reduced leaf-water potential also was different in the three species. Photosynthesis in corn was reduced whenever leaf-water potentials decreased, whereas photosynthesis in soybeans was unaffected by leaf-water potentials as low as -11 bars. In corn, however, the percentage of inhibition of photosynthesis was still much less than that of enlargement. The behavior of respiration rates during desiccation did not differ significantly for the three species. Other data show the photosynthetic rate of sorghum was still 25% of maximum at -11.5 bars, whereas corn had wilted and photosynthesis had ceased at this water potential. Slatyer (1955) reported that growth rate in sorghum was much less affected by severe stress than was growth rate in cotton and peanuts. There are definite differences between species in how they respond and different plant functions respond differently.

When Klepper *et al.*(1975) measured the diurnal pattern of plant water potential they did not find a zero water potential. Using a rhizotron where soil water at all depths was greater than -1 bar, they found a typical midday decrease in the plant water potential (Figure 7). With water limiting, the water potential was lower (higher negative value) at all times of the day than when soil water was not limiting. The plants did not completely recover, and the water potential never reached -3 bars. On a cloudy day when soil water was not limiting, the same midday dip occurred as for a clear day, but it was smaller. Under the conditions of limiting soil water, the shape of the curve should vary with the atmospheric demand. They have proposed a cutoff for N metabolism of -5 bars (Figure 7). This would indicate a midday cutoff, even with water not limiting; and where soil water was limiting, it could completely cut off N metabolism. Using a photosynthesis cutoff of -15 bars, there would be no reduction of net photosynthesis for the nonlimiting water situation, but a large reduction when water was limiting. The cutoff for transpiration should be at about the same level as for photosynthesis. If we are to understand the yield variability produced by moisture stress, we need to understand how the different physiological processes for different species, and even varieties within the species, are affected by moisture stress.

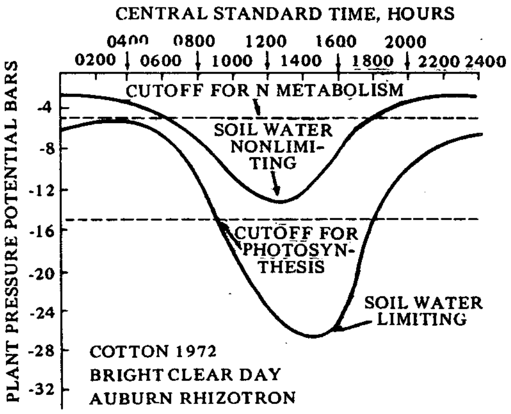

Fig. 7. Plant pressure potential in cotton for a clear day. (From : Klepper et al., 1975.) (Private communication)

The following discussion will center on the yield reduction in corn, a determinate flowering crop, and soybeans, as an indeterminate flowering crop, although some soybeans are determinate. I have also included a figure for rice.

Shaw (1975) has summarized the results of a number of researchers as to the effect of stress on corn yield (Robins and Domingo, 1953; Denmead and Shaw, 1960; Wilson, 1968; Claassen and Shaw, 1970; and Mallet, 1972). In these experiments, corn was grown with a restricted root area and kept well watered, except when stress was imposed. The treatments generally subjected the plants to 4-6 days of rather severe stress, but the exact degres of stress varied. The results of all these experiments are summarized in Figure 8. The hatched area represents the range of yield reduction, expressed in terms of percentage reduction per day of stress. The line within the hatched area represents the average yield reduction.

Yield reduction during the late vegetative stage average 2-3% per day of stress. Denmead and Shaw (1960) found that with somewhat limited leaf area, this yield reduction was due to leaf-area reduction. With a higher leaf-area index, the effects of stress

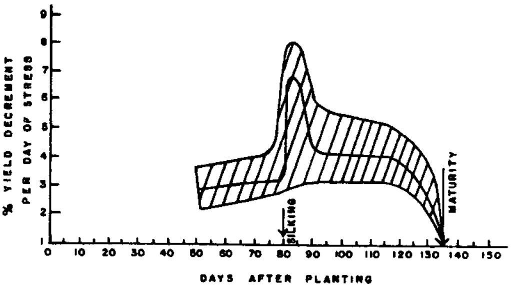

Fig. 8. Schematic diagram of relationship between age of crop and percentage yield decrement due to one day of moisture stress. (From: Shaw, 1975.)

should be reduced. Stress during the tasseling-silking stage causes a large reduction in yield. Under natural conditions, this will probably be a combination moisture-fertility stress, since stress conditions normally develop over time and result in a dry zone in the upper root zone where nutrients are frequently concentrated. In container experiments, where the stress condition can be quickly developed, the yield reduction was less if the plant had good fertility conditions up to the stress period, compared with plants that had relatively poor fertility just before the stress condition. After silking and during ear development, stress effects may be near 4% per day of stress, with the effect decreasing as maturity is approached. On a determinate crop, such as corn, the timing of the stress, as well as the intensity of it are both important in determining the yield reduction, and the magnitude of yield variability.

Shaw and Laing (1966) reported on a moisture-stress experiment on soybeans, where stress was applied at various stages of development. As can be seen from Figure 9, the number of pods, beans per pod, and seed size are all affected, but compensatory effects are found when stress is applied during flowering. The greatest yield reduction occurred when stress was applied in the filling stage, a different stage than for determinate flowering corn. The total yield reduction for each period of stress is shown in Figure 1

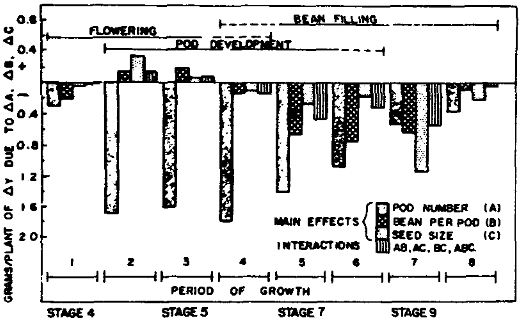

Fig. 9. Change in soybean yields due to change in pod number, beans per pod, seed size, and interactions, when stressed at selected periods of growth. (From: Shaw and Laing, 1966.)

Moisture stress applied during fertilization, or the early reproductive period, has been shown to reduce the yield of other crops. Asana and Saini (1958) observed a marked yield reduction in wheat when moisture deficiency occurred during the heading period. Van der Paauw (1949) found the greatest yield reduction in oats occurred when moisture stress was imposed during panicle emergence. Schreiber and Stanberry (1965) found the maximum yield reduction in barley occurred when it was stressed at pollination. Matsushima (1968) has shown the time near heading to be the most sensitive for rice. Figure 11 illustrates the effect of stress on rice yield. Wheat and barley would be expected to have similar responses.

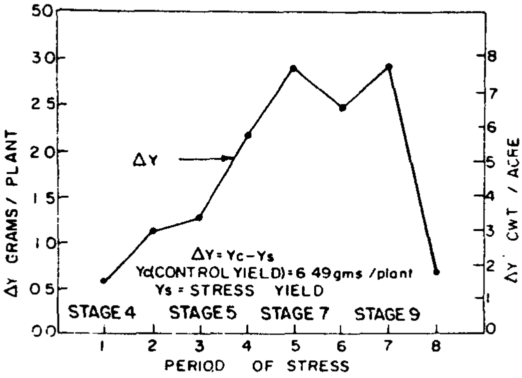

Fig. 10. Change in soybean yields due to moisture stress applied at selected periods of growth. (From: Shaw and Laing, 1966.)

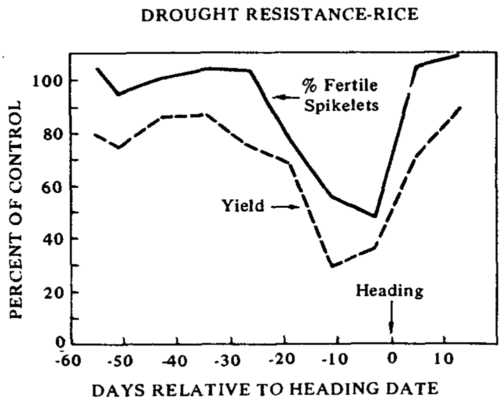

Fig. 11. Effects of 3 days of drought on yield and percent fertile spikelets of an indica rice variety (From: Matsushima, 1968).

Effects of Excess Moisture

Too much water may be almost as harmful as too little. The most injurious aspects of excess moisture are lack of aeration and reduction in the oxygen supply, which results in poor nitrification, among other effects. Aeration is also highly important because of its effect on aerobic metabolism and consequent uptake and accumulation of nutrientions in roots. microbial activity in an anaerobic environment may have some deleterious effects on root growth. High soil moisture may also have an effect on disease damage. It may also affect spring establishment of legumes and grasses. An excess of moisture later in the season may affect flowering and seed set and reduce the quality of seed.

An area does not have to be flooded for detrimental effects to occur. There seems to be relatively little quantitative data on this, possibly because of the problems in trying to define the wet status. One example will be shown to point out that these effects can occur. Shaw (1974) has developed a stress index that relates dry conditions during a period from 40 days before silking to 45 days after silking to the yield reduction. In developing this index, it was observed that, for years with low stress-index values, some yields were low relative to what would be expected, if only dry-stress conditions were considered. An examination of the soil-moisture data for these years indicated higher amounts of percolation of water through the soil (as estimated from a soil-moisture prediction program). An example of this is shown in Figure 12. The experimental farm referred to is in the northwestern part of Iowa, but not in the extreme northwestern corner. The 2 years that had significant excess moisture, but no ponding for any length of time, had low stress indexes and yields well below the predicted value. Yields in these 2 years were obviously reduced by the wet condition. In wetter areas these conditions occur much more frequently.

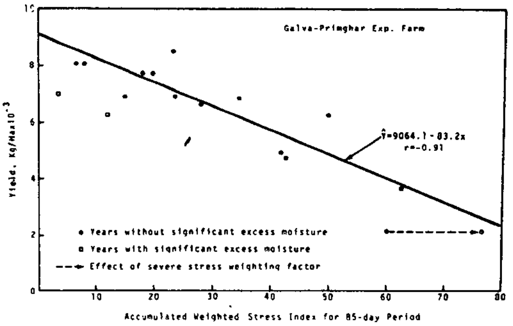

Fig. 12. Comparison of weighted stress index and corn yield at Galva-Primghar Experimental Farm, northwestern Iowa (From: Shaw, 1974).

Precipitation is one of climate's most variable parameters and introduces significant variability into crop production. With irrigation we can control some of this variation. We must fully understand how excess or deficient moisture affects crop production if we are going to modify the plant to better fit the environment and reduce this variability.

Temperature

Temperature can cause variations in crop production by directly affecting a physiological process of the plant, by affecting the length of the growing season, or by indirect effects such as smothering and heaving. The effects may be different for a fall-seeded crop, compared to a spring-seeded crop.

Fall Seeded Crops

In the U.S., winter wheat is sown from September through much of the fall period. In the western wheat areas optimum seeding date is when the mean temperature is from 50 to 60°F. If sown too early the limited moisture supply may be exhausted, root rots are more prevalent and the crop is somewhat subject to winter injury. If sown too late there will be fewer tillers and winter injury is most likely. Fall precipitation is more closely related to yields than is spring precipitation. In the eastern and wetter areas the sowing date is tied very closely to the Hessian fly-free date. Sowing needs to be early enough so that plants will become well rooted before growth ceases in the fall to reduce injury due to heaving.

Winter injury may be caused in four ways:

1. Direct injury by freezing of tissue
2. Indirect heaving injury.
3. Indirect smothering injury.
4. Direct physiological drought.

In drier regions, the most critical aspects of winter temperatures are related to cold hardening. Winter cereals in the tender stage are no more cold tolerant than spring cereals. Unhardened plants may be injured by exposure to temperatures of near 0°C (Gusta and Fowler, 1971) but with any degree of hardening will not be injured until temperatures reach -5 to -10°C; while cold hardened plants may survive temperatures of -30°C, and down to -40°C with snow cover. Young plants of wheat and barley do not die as long as the crown is alive, and it is about 1 inch below the ground surface. Even a few hours of near freezing temperatures increase the ability to survive cold temperatures, but hardening is also related to moisture and light. If exposed to temperatures warm enough for growth to begin again, hardy varities completely lose their "winter hardening". Cold weather late in the winter may be most damaging, as plants are decreasing in their hardiness. Winter wheat is more resistant to cold than winter barley.

The indirect effects (smothering and heaving) are more important in wetter areas where considerable precipitation occurs during the winter months. Your relatively dry winters should reduce this type of injury. Drought injury may occur if conditions get very dry.

Early winter wheat may come into head before the last spring freeze has occurred. Even a light frost can damage the flower.

Spring-Seeded Crops

Spring-seeded crops may be a relatively short-season crop (oats, wheat, barley) or a relatively long-season crop (rice, corn). The short-season cereals are usually not severely injured by an early-season freeze. Even corn can be frozen off above the ground when small with little effect on the final yield if the growing point is not damaged. Apparently rice is the most sensitive of the crops mentioned. With the short-season cereals, early seeding generally gives the highest yields. For oats, I have found a positive correlation between temperature at planting and the final yield, and would expect a similar relation for most other spring seeded cereals.

Cold temperatures during the growing season have two effects: a) a direct effect on a physiological process, or b) a change in the time of maturity. For short-season crops a delay in maturity may result in heading occurring in a higher temperature period, usually reducing yield in the U.S. For long season cereals, a delay in maturity may mean freezing damage before maturity is reached.

For long-season crops, temperature summations (growing-degrees, heat units, etc.) are a good means of evaluating the stages of development. A positive summation of temperature above a selected base temperature over a designated period of development has been proposed as a measure of thermal activity. It is used to relate to progress, but may not be well-related to yield. The first such relation-ship was developed by Reamur about the middle of the 18th century, with many methods developed since then. The base temperature used represents the point of zero development of the plant. Many of these methods do not evaluate the various temperature magnitudes and durations in accordance with true physiological effects. Some assume a linear response, others curvilinear. Many do not impose any limitation on high temperatures. Soil fertility, soil type, moisture conditions, and various other weather and disease factors all may have some effect on the summation. As Nuttonson (1953) noted, a wide variety of synonymous terms are found in the literature denoting "heat" requirement of crops. Thus, the term degree day, thermal unit, heat unit, and growing degree day, or unit, have all been used to designate one degree of daily mean temperature above a base temperature. Heat units are a misnomer and should not be used for temperature summations.

In spite of their limitations, these methods have found considerable usefulness. They are not an absolute value; i.e., the stage of development of a variety will not be a constant number of growing degree units, but will show some variation for different locations, seasons, or even planting dates within the same year. Different base temperatures may give the highest correlations for different stages of development (Aspiazu and Shaw, 1972). Growing degree units, however, are much more constant for most stages of development than are calendar days, and provide us with the bast means of rating crop progress relative to normal conditions. This information is particularly useful when cool spring temperatures have delayed progress so that fall-freeze injury probabilities are increased. One of our major problems with cool spring temperatures is the problem created by delayed maturity and freezing injury in the fall before maturity occurs.

Every physiological process has a more or less well defined range of limits of tolerances. There are minimum, optimum, and maximum temperatures for plant activity. These points are defined as the cardinal temperature points. These values are not absolute and should be considered relative values only. The extremes do not represent sharp cut-off points. They may vary widely with the stage of development of the plant and also vary between species. Conditioning of the plant may affect the value. For more detailed information the reader is referred to Levitt (1972), or Mussell and Staples (1979). Excellent, detailed reviews covering this area, or portions of it, are found in those references.

The date of planting reflects the response of the particular seed to temperature and the length of the growing season available to grow the crop. With a limited growing season, planting tends to be done at slightly lower temperatures. Spring wheat is planted when the daily mean temperature is 3-4.5°C (37-40°F), while corn is planted when the mean temperature is 13-14°C (55-57°F), and cotton 17-18°C (62-64°F).

For most temperate-zone crops, the optimum temperature for growth ranges from 24-29°C (75-85°F), with a maximum of 35-40°C (95-105°F), For corn, the minimum temperature for appreciable growth is 10°C (50°F), the optimum near 30°C (86°F) and the maximum approximately 45°C (113°F). The maximum values are particularly affected by the available soil-moisture content. The maximum temperature for growth may be considerably less than the temperature that causes heat damage, and the lethal temperature will depend upon the duration of that temperature.

Chilling injury can occur during the warm season of the year, when temperatures do not have to be below freezing for injury to occur to some plants. Plants of tropical origin (sorghum, rice, corn, sugar cane) can be injured by temperatures above freezing. Sellschop and Salmon (1928) showed that exposures to temperatures of 0° to 10°C (32°F to 50°F) can result in yellowing of leaves, dead areas on leaves, dropping of leaves, and even death of some tropical and subtropical plants.

Temperatures of 60-70°F are favorable for active spring growth for most crops. Early season temperatures usually show little correlation with final yields. To determine what the effects might be, one needs to examine the temperatures which occur and compare with how the plant responds to different temperatures. In the Corn Belt, where temperatures at planting are usually below optimum, a practice which leaves corn stalks on the surface

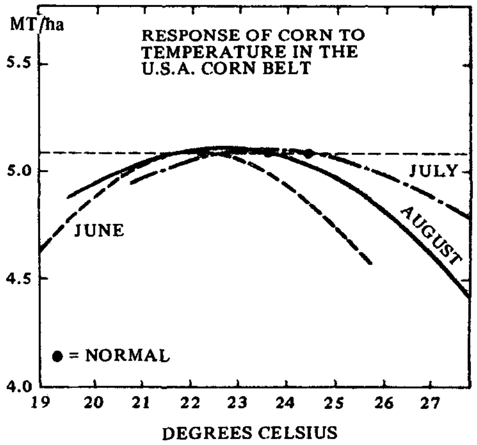

Fig. 13. Average response of corn to summer temperature in five Corn Belt states (Thompson,, 1963).

and cools the soil further, will be detrimental to crop progress. In the southern U.S., where temperatures are more near optimum, the effect is minimal. Thompson (1963) (Figure 13) has analyzed monthly temperatures in the Corn Belt in relation to corn yield. Normal temperatures for June are near optimum, but a noticeable yield reduction is observed if temperatures are considerably cooler than normal. July and August temperatures are above optimum, so cooler temperatures are beneficial and above normal temperatures detrimental. Our July and August temperatures rarely get cool enough to be detrimental. Rice apparently is much more sensitive to cool temperatures which occur more often in your area. Inoue *et al.*(1965) stated that in Japan, damage often occurs in the cool area because of a chilly summer.

In much of the U.S., detrimental summer temperatures are nearly always on the high side. High temperatures, usually combined with soil moisture shortages can be very detrimental to yields. I found a very high negative correlation between oat yields and temperatures near heading over the Midwest U.S. Climatologically, that is our major problem. Your climate, combined with the sensitivity of rice to cool temperatures, creates quite a different climatic problem. We need to develop good temperature-yield relationships for different crops in the different climate areas. Climate-wise, a 50% departure from the mean for precipitation may not be very unusual, but temperature departures of that magnitude do not occur. Climate-wise we are dealing with a much more stable parameter when we consider temperature.

High temperatures may permit survival of the plant, but may alter its growth. When testing the effects of high temperatures it is difficult to separate these effects from those attributable to associated conditions, notably available soil moisture. Many times these effects are combined.

There are other environmental parameters that affect yield that I have not discussed: soil temperature (highly correlated with air temperature), relative humidity, wind, and such atmospheric parameters as ozone and acid rain. Generally, little information is available to relate these to yield variability; and time does not permit discussing them.

EFFICIENCY

I have not discussed the "efficiency" of production. This could be considered as the "economic efficiency", or the "weather efficiency". By the latter I mean making the most out of the weather we have. If we do that we might well have the highest "economic efficiency", but that subject is so involved I will not even attempt to discuss it. I will briefly look at certain aspects of "weather efficiency"

In regions where no more land is available for cultivation, the only way left to increase production is to obtain more efficient production per unit of land area that can be cultivated. One approach to this has been proposed in India (Kanwar, 1972), where national cropping patterns have been proposed, in that the crops most efficient for an area would be concentrated in those areas. Soil and climate zones were jointly used to do this. A water balance equation was used to divide the country into eight moisture zones. In addition, five temperature zones were determined by using the mean annual, or seasonal temperatures. These were superimposed over the 14 most important soil groups of India.

An analysis of the productivity efficiency of various crops in different states was made by making use of the relative average yield index and relative spread index of the crop.

Relative yield index =

$$\frac{\text{Mean yield of crop in district or groups of districts}}{\text{Mean all-India yield}} \times 100$$

Relative spread index =

$$\frac{\text{Area of crop expressed as \% of total cultivated area in zone}}{\text{Area of crop expressed as \% of total cultivated area in India}}$$

x 100

These indexes were grouped into seven categories

Table 2. Scheme for productivity rating of different zones (from Kanwar, 1972).

	Relative yield index					
Relative spread index	200%	200-150	150-120	120-90	60-30	30
A 200%	Zone I				Zone III	
B 200-150	Yield high				Yield low	
C 150-120	Spread high				Spread high	
D 120-90						
E 90-60	Zone II				Zone IV	
F 60-30	Yield high				Yield low	
G 30	Spread low				Spread low	

and arranged in a two-way table as shown in Table 2. Zone 1 is considered the most efficient; Zone IV, the most inefficient.

The different soil and climatic zones are shown in Figure 14. The moisture and temperature zones are for the karif season. Similar maps were presented for an annual basis and for the rabi season. For every important crop, the most efficient region can be identified and the crop rotation woven around it. This will determine the most suitable crop pattern. The zones that seem to be inefficient for a crop need to be identified, and more efficient crops substituted.

The most efficient zone for wheat production is shown in Figure 15. This zone is on the alluvial soils of Punjab, Haryana, Western U.P., and Rajasthan. The most efficient zone of wheat production lies in the rabi termperature belt of 10-20°C and a moisture regime belt of 60-80 percent deficit. The yields of wheat are dependent upon supplemental irrigation. Encouragement of wheat production in this area will help increase national production. Kanwar stated that this area could quadruple its wheat production if necessary seed, fertilizer, and

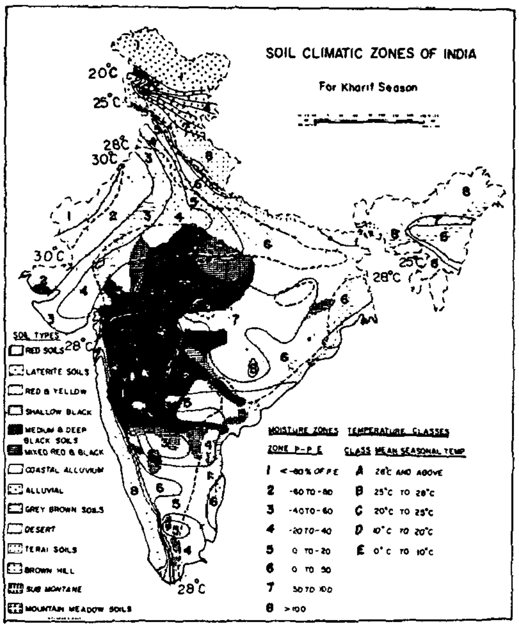

Fig. 14. Soil and climatic zones of India (From: Kanwar, 1972).

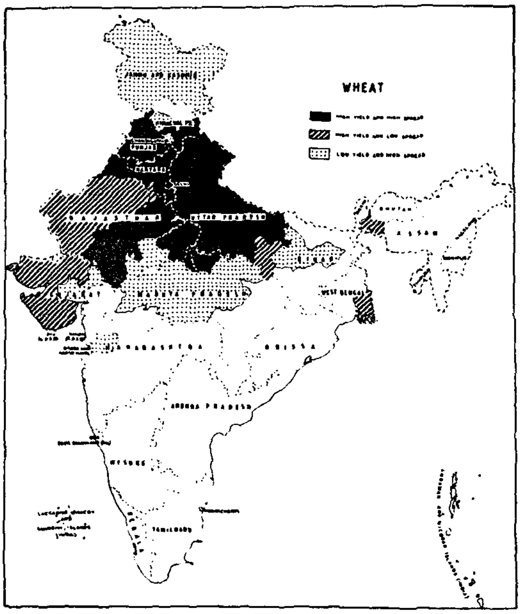

Fig. 15. Most efficient zone of wheat production in India (From: Kanwar, 1972).

irrigation water were made available The high yield-low spread zone has a high yield potential, but little wheat is grown because of the lack of water. Irrigation development in this area is important. Production of wheat in zones 3 and 4 (Table 2) should be encouraged only where it comes in rotation as a short-duration crop without competing with the most efficient crop of the zone.

The most efficient zones for corn are the hilly and sub-montane tracts of Northern India and parts of Rajasthan and Bihar (Figure 16). It has good possibilities in many parts of south India under well-drained conditions and can be grown as a corn-wheat rotation in the wheat crop zone.

Maps such as those shown in Figures 15 and 16 were developed for 10 different crops. These were then combined to designate the most efficient crops (up to three) for the different areas of India. There were some zones that did not show any efficient cropping system.

There is one problem that should be recognized in an approach such as that just shown. Although the variation in yields for most years may be small, because of the limited geographical area in which the crop is grown, major fluctuations of critical weather parameters in the area could cause major fluctuations in the total production of a crop. If two or three areas where a crop is grown are widely dispersed, this type of variation should be greatly reduced.

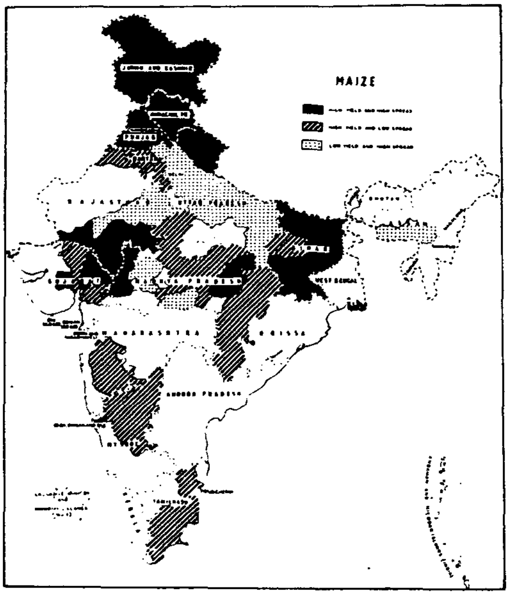

Fig. 16. Most efficient areas of maize (Hilly and submontane tracts of northern India, and parts of Rajasthan and Bihar) (From: Kanwar, 1972).

Only the future will show how successful such a program could be, but it is one approach for making maximum use of the natural resources (soil and climate) of a country.

REFERENCES

1. Asana, R.D., and A.D. Saini(1958) Studies in physiological analysis of yield: IV. The influence of soil drought on grain development, photosynthetic surface and water content of wheat. Physiol. Plant. 11:666-674.
2. Aspiazu, C., and R.H. Shaw(1972) Comparison of several methods of growing degree unit calculations for corn (*Zea Mays* L.). Iowa State J. Sci. 46:435-442.
3. Billings, W.D.(1969) Plants and the ecosystem. Wadsworth Publ. Co., Inc., Belmont, CA.
4. Boyer, J.S.(1970) Leaf enlargement and metabolic rates in corn, soybean, and sunflower at various leaf water potentials. Plant Physiol. 46:233-235.
5. Claassen, M.M., and R.H. Shaw(1970b) Water deficit effects on corn: II. Grain components. Agron. J. 62:652-655.
6. Denmead, O.T., and R.H. Shaw(1960) The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52:272-274.
7. Denmead, O.T., and R.H. Shaw(1962) Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 54:385-390.
8. Gusta, L.V., and D.B. Fowler(1979) Cold resistance and injury to winter cereals. pp. 159-

178 *In* Stress Physiology in Crop Plants, Eds. Mussell and Staples.

9. Inoue, E., Y. Mihara, and Y. Tsuboi(1965) Agrometeorological studies on rice growth in Japan. Agr. Meteorol. 2:85-107.
10. Institute of Crop Ecology, Charles F. Kettering Foundation(1976) Impact of Climatic Fluctuation on Major North American Food Crops.
11. Kanwar, J.S.(1972) Cropping patterns, scope, and concept. pp. 11-38. *In* Proceedings of the Symposium on Cropping Patterns in India. Indian Council of Agricultural Research.
12. Levitt, J.(1972) Responses of plants to environmental stresses. Physiological Econogy Monography. Academic Press. New York.
13. Mallet, J.B.(1972) The use of climatic data for maize yield predictions. Ph.D. Thesis. Dept. of Crop Sci., Univ. of Natal, Pietermaritzburg, South Africa.
14. Matsushima, S.(1968) *In* Proc. Crop Sci. Soc. Japan (Special Issue). Rice cultivation in Southeast Asia. pp. 102-109.
15. Mussell, H. and R.C. Staples(1979) Stress physiology in crop plants. Wiley Interscience, New York.
16. National Research Council(1976) Climate and Food. Climate Fluctuation and U.S. Agricultural Production. A report of the "Committee on Climate and Weather Fluctuations and Agricultural Production". Board on Agriculture and Renewable Resources. p. 23.
17. Nuttonson, M.Y.(1948). Some preliminary observations of phenological data as a tool in the study of photoperiodic and thermal requirements of various plant material. Vernalization and photoperiodism. A. Symposium. pp. 129-143. Chronica Botanica, Waltham, MA.
18. Robins, J.S., and C.E. Domingo(1953) Some effects of severe soil moisture deficits at specific growth stages in corn. Agron. J. 45:618-621.
19. Schreiber, N.A., and C.O. Stanberry(1965) Barley production as influenced by timing of soil moisture and timing of nitrogen applications. Agron. J. 57:442-445.
20. Sellschop, J.P.F., and S.C. Salmon(1928) The influence of chilling above the freezing point on certain crop plants. J. Agric. Res. 37:315-338.
21. Shaw, R.H., and D.R. Laing(1966) Moisture stress and plant response. pp. 73-94. *In* Plant Environment and Efficient Water Use. W.H. Pierre, D. Kirkham, J. Pesek and R.H. Shaw (Eds.). Amer. Soc. Agron. and Soil Sci. Soc. Amer., Madison.
22. Shaw, R.H.(1974). A Weighted moisture-stress index for corn production in Iowa. Iowa State J. Res. 49:101-114.
23. Shaw, R.H.(1975) The climatic requirement of corn. *In* Corn and Corn Improvement. Agron. Monograph. G. Sprague (Ed.). pp. 591-623.
24. Thompson, L.M.(1963) Weather and technology in the production of corn and soybeans. Cen. for Agric. Econ. Development. Rep. 17, Iowa State Univ., Ames.
25. Van der Paauw, F.(1949) Water relations of oats with special attention to the influence of periods of drought. Plant Soil 1:303-341.
26. Wilson, J.H.(1968) Water relations of maize: I. Effects of severe soil moisture stress imposed at different stages of growth on grain yields of maize. Rhod. J. Agric. Res. 6:103-105.

DISCUSSION

Question (Mr. Kwang-Sik Kim, Director of Forecasting Bureau, Central Meteorological Office)

Our government has made many efforts in order to be self-sufficient for staple food (mainly rice and barley), and for this, at present time, the currently proceding projects are the fields on crop cultivation, soil improvement, and irrigation, i,e.; 1) Selection of better varieties for higher food production and also for insect-pests resistance, cold or chill resistance, and dry resistance, 2) Expansion of irrigation facilities etc. But we could not get good results with above items because we could not overcome the instability of crop yield. I guess one of the most important reasons which we can not approach to our goal is the deficiency of the basic studies on environmental climate. In such a viewpoint I agree to your opinion absolutely which you expressed through your papers about effects of Climatic Condition on Stability and Efficiency of Crop Production.

In addition, our country has very complicated topography and shows great differences of agriculural climate according to localities. In order to improve the stability of crop production, therefore, I guess we must try to make the agricultural climate-classification on land presently being cultivated. Would you please show me your opinion?

Answer (Dr. R. H. Shaw)

With the extremely variable topography in Korea, I would say that it is essential that you have an agricultural climate of lands. The local climate can be different on opposite sides of a valley, depending upon the exposure to solar radiation. The climate on the other side of the mountain can be very different or it may have areas with similar climates. The microclimate will vary tremendously in your complicated topography due to elevation and exposure to sun and wind. It is very important that the agriculturists work with the meteorologists to expand the meteorological observations of greatest importance to agriculture and develop the agricultural climate classification of land.

Question (Dr. Suk-Soon Lee, Yeongnam University)

Generally yield potential of late maturing rice varieties or indica/japonica rice varieties is higher, but yield is less stable compared to early maturing or japonica type rice varieties due to occasional low temperature at the reproductive stage in Korea. Under such unpredictable weather conditions, do you think, should we plant late maturing or indica/japonica rice varieties with some risk of low temperature damages for a possible higher yield?

Answer (Dr. R. H. Shaw)

As we say in the U.S., this is a $64,000 question-one very different to answer, but the answer is very important to Korea. You need to develop models which predict what the different rice yields will be in different years and then examine the results for a period of years to get good estimates of what the variation will be. The decision of what to plant is not a decision for agriculturists alone. It involves economic factors in your country. Is it better to go for a more moderate yield, planting at least some of the less sensitive varieties, and not suffer the extreme variation in a year when low temperature is a severe problem, or is it better to have higher yields in most years but in "bad weather" years have a major disaster in the rice yield? That decision needs to be made by high-level administiations. In the meantime, crop scientists need to keep working and develop the new varieties to be more cold weather resistant.

Question (Dr. Suk-Soon Lee)

In one of your research bulletins the north central region of USA was devided into several parts according to growing degree days to recommend corn hybrids with optimum maturity in the region. If we try to apply similar approaches to rice in Korea, what factors, do you think, should be considered?

Answer (Dr. R. H. Shaw)

I believe that methods which allow us to project different stages of crop development are very important for long season crops. Corn and soybeans have been studied very much in the U.S. Temperature is the most important factor, but solar radiation should also be included. Information on the length of different phenological periods, and the growing degree day (or some such unit) needs to be developed for your late maturing rice varieties. Thank you again for inviting me to Korea.