AN ABSTRACT OF THE THESIS OF

Raul Jose Agamennoni for the degree of Master of Science
in Crop Science presented on October 13, 1983
Title: THE EFFECT OF FERTILITY LEVEL ON PLANT GROWTH AND
DEVELOPMENT, WATER UPTAKE AND WATER STRESS
IN DRYLAND WHEAT PRODUCTION
Abstract approved: Redacted for Privacy
Floyd E. Bolton

Dryland winter wheat in eastern Oregon is usually subjected to water stress several times during the growing period. Moreover, the last three months of growth period depend strongly on the available soil water. The fertility level, stage of growth, availability of soil water and climatic conditions all interact to determine the severity of crop water stress. The level of nitrogen and phosphorus fertility in the growing wheat crop can affect plant growth and development, water uptake and the incidence and severity of water stress. In order to gain a better understanding of the complex interactions leading to water stress in the wheat crop, a means of determining when and how long the stress occurs is needed. The Crop Water Stress Index (CWSI) developed by Idso et al in 1981 utilizing the infrared thermometer was used to determine the crop water stress level during the critical spring growth period.

The objectives of this work were: (1) to study the effect of N and P fertilization levels on crop water stress and water uptake by the crop; (2) to describe the crop water stress phenomenon in order to help explain when, and why water stress occurs; (3) to analyze the dry matter production and partitioning and yield components as

related to fertilization, crop water stress and date of planting; and (4) to attempt to develop an equation to predict grain yield of soft white winter wheat in Oregon, given a certain level of water stress assessed by the CWSI.

Two types of field fertilizer experiments were conducted using a soft white winter wheat cv. Stephens at the Sherman Experiment Station, Moro, Oregon during the 1982 and 1983 seasons.

Atypical climatic conditions with precipitation and relative humidity levels greater than, and maximum temperatures less than the long-term means combined to produce a relatively low level of crop water stress. There were two relatively short periods in 1982 in which moderate to severe crop water stress occurred. The CWSI proved capable of detecting the severity and duration of these stress periods with a good level of reliability.

Nitrogen fertilization increased the total crop water uptake. Coincidentally, CWSI level was always reduced with the addition of N. The only exception was in one N experiment in 1982, in which water uptake was not increased with N fertilization.

The total dry matter production and yield relationship was indicative of the climatic conditions which produced nearly optimum soil water conditions in the 1982 and 1983 seasons.

Nitrogen increased total dry matter production during both seasons, with a higher level being evident in 1983.

The yield increase from the added nitrogen was mainly due to an increase in spike number and to a lesser extent an increase in the number of kernels per spike.

Late plantings produced larger individual spikes with a greater number of kernels than earlier seeding , but these differences were not great enough to overcome the drastic reduction in spike number.

A logarithmic relationship between grain yield and the CWSI averaged on a daily basis was developed. Although somewhat inconsistent, the need to account for other factors such as N availability and the differences in vegetative growth produced before the period of CWSI study, was recognized. The assumption that CWSI alone could predict grain yield was originally based on limited soil water conditions. If that condition is not present , the other variables that may limit yield potential must be considered.

The use of infrared thermometry technology and the CWSI system appear to be feasible tools to determine crop water stress at the field level. However, one can expect more consistent and reliable results under the more normal stress conditions.

THE EFFECT OF FERTILITY LEVEL ON PLANT GROWTH AND DEVELOPMENT, WATER UPTAKE AND WATER STRESS IN DRYLAND WHEAT PRODUCTION

by

Raul Jose Agamennoni

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

completed October 13, 1983

Commencement June 1984

APPROVED:

Redacted for Privacy

Professor of Crop Science in charge of major

Redacted for Privacy

Head of Department of Crop Science

Redacted for Privacy

Dean of Graduate School

Date thesis is presented October 13, 1983

Typed by Hugh Butler for Raul Jose Agamennoni

DEDICATION

This thesis is dedicated to my wife Silvia,
my son Hernan and my daughter Analia

who shared with me the remarkable humid experience
of studying dryland farming in small pleasant Corvallis.

ACKNOWLEDGEMENTS

My deep appreciation and gratitude to my adviser Dr. Floyd E. Bolton is extended for his guidance, help, objective criticsm and patience. I wish also to give grateful recognition to Dr. David M. Glenn, who was my first adviser, for his help, encouragement and assistance in planning and conducting the first year of the research program.

I should also extend special thanks to Dr. Willis L. McCuistion, Dr. Neil W. Christensen and Dr. Frank Conklin for their friendly help and for serving on my graduate committee.

Special recognition goes to Joe C. Kenworthy who took daily readings with the infrared thermometer on the experiments.

Many other people have given their time and knowledge and should recieve due recognition: Dr. Larry L. Boersma, Dr. Hugh E. Gardner, Dr. David B. Hannaway, Dr. Dale N. Moss, Dr. David G. Neiss, and Dr. Roger G. Petersen.

Sincere appreciation for the help and friendship are also extended to the following graduate students: Mylen G. Bohle, Hugh Butler, Albert Fischer, Ariel Lorenzo, Pable Ott and Luiz G. Vieira.

Finally I wish to express my gratitude to the Instituto Nacional de Tecnologia Agropecuaria (INTA), Argentina who provided all the financial assistance in this graduate program.

TABLE OF CONTENTS

LIST OF FIGURES

Figure | Page

LIST OF TABLES

Table Page

LIST OF APPENDIX TABLES

THE EFFECT OF FERTILITY LEVEL ON PLANT GROWTH AND DEVELOPMENT, WATER UPTAKE AND WATER STRESS IN DRYLAND WHEAT PRODUCTION

INTRODUCTION

In eastern Oregon dryland areas, soft white winter wheat production is an important agricultural activity. Soil nitrogen is known to be a widespread limiting factor. Precipitation during the cooler months of the year permits a very high efficiency in soil water stored under fallow systems.

However, this region has a wide range in soil depth, from 0.45 to 6.00 m and total amount of annual rainfall, from less than 250 mm to more than 500 mm, which in turn greatly determines the amount of soil water stored.

With the exception of the Pendleton area, where annual cropping system is generally economically feasible because of higher rainfall, the remaining area requires two years for each harvested crop.

This is accomplished by using a summer fallow system which enhances moisture infiltration and maintains the soil water stored during the first year by avoiding soil water evaporation during the summer with a stubble or dust mulch.

The Walla Walla soil series is one of the more prevelent soil types where wheat is produced in this area. This soil series is generally well drained, with a uniform texture (silt loam) throughout the profile, with the exception of the upper layer which presents some variability (Robinson, 1961).

This study was confined to this particular soil series, and the work was conducted at Sherman Exp. St. Moro, Oregon. Most (78%) of the precipitation at this location falls in the period from October through April with an annual average of 289 mm.

Plant water stress is one of the most common causes of yield reduction, because the last 3 months of wheat growth (May-June-July) strongly depends on stored soil water.

In a deep soil (Walla Walla series) there is some evidence that not all the available soil water is used. Thus, creation of an extensive root system by modifying agronomic practices including fertilization might be a way to increase water uptake, to lessen intensity and duration of plant water stress and to increase yield.

There is some evidence that balanced fertilization with nitrogen and phosphorus could improve earlier root development (Glenn 1981b).

Hence, the level of fertility, stage of growth, availability of soil moisture and climatic condition all interact to determine the severity of the crop water stress. In order to gain a better understanding of the complex interactions leading to water stress in the wheat crop, a means of determining where and how long the stress occurs is needed.

During the last 20 years, the infrared technology has developed rapidly. Today we have available a portable and reliable infrared thermometer that permits crop canopy measurement in the field in a rapid and integrated manner.

In the last 5 years, that infrared thermometry technology has made possible significant advances in the development of several stress indexes. Among them Stress Degree Day (SDD) and Crop Water Stress Index (CWSI) have been studied and tested in several crops and different environments in the U.S.A.

The concept involved is as follows: transpiration cools the leaves below the air temperature. As water becomes limiting transpiration is reduced and the leaf temperature increases. The development of a portable and reliable infrared thermometer to measure leaf temperature combined with the development of an index like CWSI, is expected to provide a better comprehension of crop water stress problems at the field level.

Therefore, a study of the crop water stress under field conditions was conducted using these new tools (infrared thermometer and CWSI) during two growing seasons (1981-82 and 1982-83) and two field experiments with fertilizer treatments.

These studies were carried out to achieve the following objectives:

1. Determine the effect of nitrogen and phosphorus fertilization treatments on crop water stress in relation to crop water uptake from the soil.

2. Describe the crop water stress process in order to attempt to understand, when and why water stress occurs.

3. Analyze dry matter production and partitioning and yield components in relation to fertilization and crop water stress.

4. Develop a predictive equation for soft white winter wheat grain yield in the dryland region of eastern Oregon under a given set of climatic conditions.

LITERATURE REVIEW

1. Root Development and Water and Nutrient Uptake.

Plant roots have several functions including water and nutrient absorption, and anchorage as well as synthesis of organic compounds. Water and nutrient uptake are of primary interest in this study.

Kramer and Coile (1940) stated that under unsaturated soil water conditions, capillary movement of water toward the roots is not significant. Thus, continual growth of the roots into new regions of the soil profile is essential for adequate water absorption and supply (Kramer and Coile 1940).

The nature of the root system is a very important factor in determining the relationship between plant water deficits, growth and soil water content. The surface of water absorption provided by the root system of the plant can play a key role in the plant-water balance. If the plant has a large root density and deep root zone for water absorption the probability of plant water deficits is greatly reduced (Vaadia et al 1961; Slatyer 1967).

Plants with a greater root system have more water available and need lower rates of water uptake per unit length of root (Gardner 1960a). This means that these plants need to develop smaller negative value of plant-water potential to take up the same amount of water as plants with less developed root systems.

Hurd and Spratt (1975) have indicated that, in general, cereals have an extensive root system with a low water flow rate into the roots per unit of length. Furthermore, they found that the increase in water deficiency around the roots is much slower than in other plants. However, they felt that cereal root systems could be improved even further by breeding or agronomic practices.

It is known that the greater the depth of available soil water, the greater the root penetration. Hurd and Spratt (1975) have indicated that under semiarid conditions the root system below about 60 cm is the most important zone for drought resistance. Quite often, under semiarid conditions, the water in the first 60 cm of the soil profile is used before the grain filling stage. Therefore, the ultimate grain yield depends on the water available below this layer.

The early work of Weaver et al (1924) on wheat root systems showed that mature roots of winter wheat reached from 120 to 210 cm depth in the soil profile. Kmoch et al (1957) observed roots of winter wheat as deep as 390 cm in soil with adequate moisture at that level.

Another aspect is the active life of the root system. Under field conditions root growth in wheat may last until heading, but with adequate water and nutrients the root system development could continue well into the grain filling period (Evans et al 1973). Hurd (1968) found that roots of spring wheat decrease or stop growing at heading, especially under stress. Pinthus (1969) found the highest rate of root growth occurred during spike formation to heading period. Therefore, available moisture during this period could determine the amount of root development.

Pearson (1971) has pointed out that even in humid areas, improvement in root development and function seems to be an important factor to mitigate occasional water deficiencies and increase yields. In general, shallow rooting increases the drought hazard to crops. Thus, extensive and vigorous root growth throughout the soil profile under semiarid conditions would be necessary to produce grain yields increases under limited moisture situations.

Another important function of roots is nutrient uptake. Cornforth (1968) found that the nitrogen uptake is influenced by the gross volume of soil exploited by roots, but for phosphorus uptake, root intensity (mass of roots per unit volume of soil) was more important. This might be explained because: "the volume of soil mainly contributing to the nutrition of the plant in the field is much smaller than the total volume occupied by the roots. An exception must be made for the highly mobile nutrients such as nitrate, which will be drawn toward the root surface along with the extracted water" (Wiersum 1961).

Thus, the greater the gross volume of soil explored by roots the greater the uptake of nitrogen and soil water, especially if the upper layers are drying out and there is enough moisture deeper in the soil. However, greater gross volume explored by roots may not be related with uptake of less mobile nutrients like phosphorus.

Hence, both higher gross volume of soil explored and root growth intensity would be desirable for higher soil water and nutrient uptake.

2. Nitrogen and Phosphorus Fertilization and Root Growth.

There are several studies reporting beneficial effects of nitrogen on root growth permitting the plant to extract water deeper in the soil profile.

Kmoch et al (1957) found that nitrogen fertilizer increased root weight of winter wheat and permitted more complete utilization of subsoil moisture. Brown (1972) reported that wheat plants fertilized with nitrogen extracting water down to 180 cm whereas plants without nitrogen took up water from only the upper half of this depth.

Ramig and Rhoades (1963) found under semiarid conditions, wheat with nitrogen application extracted more water from 200 cm depth than the control (no nitrogen). It is suggested that increased root growth caused by nitrogen application permitted the roots to extract water at lower water potential. In the Pacific Northwest, Koehler (1960) working in a deep Walla Walla silt loam found that nitrogen fertilization of wheat increased water uptake from deep (150-210 cm) in the profile.

Viets (1962) stated that fertilizer may increase root development making possible water extraction at lower water potential and deeper in the profile.

Hurd and Spratt (1975) have suggested that phosphorus deficiencies would reduce both root and shoot growth and increasing soil phosphorus would increase root-shoot ratio and cereal yields (small grains).

Troughton (1957) reviewed early works on the effect of phosphorus fertilization on root weight of several temperate grasses. He concluded that in some phosphorus experiments there were increased root weights while in others root weights decreased. Thus, he refused to accept the old opinion about phosphorus and its beneficial effect on roots of plants. However, he also pointed out that in most experiments, more of the control plants (no phosphorus) suffered from a severe phosphorus deficiency.

Hackett (1969a), studying deficiency effects on root growth of barley, found that the major effects were on the length and branching of the primary laterals. Although phosphorus deficiency reduced the mean length of the primary laterals by 33%, it did not prevent the formation of secondary laterals.

At the field level, Power et al (1961) found that phosphorus fertilization of spring wheat in semiarid regions of northeastern Montana did not generally increase soil moisture use at any stage of plant growth. However, phosphorus increased the yield of grain by 16% as compared with the control.

Black (1970) reported that low soil moisture, low soil phosphorus availability and low soil temperature tends to limit adventitious root formation, tillering and, as a consequence, decreased yields of wheat. He also found that phosphorus improved nitrogen uptake suggesting that it might be related to greater exploration of the soil volume by increased numbers of adventitious roots. In his work he noted that uptake of nitrogen and phosphorus was positively correlated with adventitious roots.

Nielsen (1971) pointed out that water supply, available nutrients, and root temperature strongly interact with each other. He also stated that unfavorable root temperatures can be partially mitigated if proper amounts of water and nutrients are present in the root environment.

3. Nitrogen and Phosphorus Fertilization, Water Use Efficiency (WUE) and Yield Responses.

Viets (1962) stressed the importance of the nutritional level of the plant on WUE. He stated that often times low WUE is the result of perhaps only one plant nutrient deficiency. Under nutrient deficient conditions, growth is greatly reduced, but transpiration is about the same. Hence, WUE is reduced. He also pointed out that under semiarid conditions, phosphorus fertilization generally hastens maturity, reduces evapotranspiration resulting in higher WUE.

On the other hand, nitrogen fertilization in cereals generally delays maturity, thereby increasing the evapotranspiration period. That might be desirable under humid areas to get maximum yields, but not for semiarid areas where rainfall is restricted.

One interesting difference between phosphorus and nitrogen is that the former, even under drought conditions, improved yield and rarely has been reported to decrease yield; whereas the latter, under these conditions, normally decreases yield (Russell 1967; Piper and Vries 1964).

A high rate of nitrogen early in the growing season may result in excessive top growth, exhausting soil water before the period of maximum water requirements of the plant (Arnon 1975).

However, there are many studies that have found N-P interaction probably because nitrogen often enhances the effectiveness or uptake of phosphorus (Duncan and Ohlrogge 1958; Rennie and Soper 1958; Miller 1971). Hence, proper balance of both nutrients must be achieved to obtain higher yield.

There is a general agreement among the investigators conducting research under semiarid conditions that the level of fertility (particularly nitrogen) must be adjusted to the current level of soil moisture in order to maximize the WUE.

4. Soil Fertility Status of the Columbia Basin Dryland Region.

During the past three decades several investigators (Leggett et al 1959; Hunter et al 1961; Rhode 1963 and Gardner et al. 1975) have demonstrated that applied nitrogen is required in order to achieve maximum economic grain yields in the dryland areas of the Columbia basin.

Leggett et al (1959) reported significant yield increases in 82% of 112 experiments conducted in dryland wheat in eastern Washington during 1953-1957. Hunter et al (1961) in eastern Oregon obtained significant N response in more than 70% of the 152 experiments conducted in different sites of the low rainfall areas during 1953-1957. Rohde (1963) found that moderate N application rates increased numbers of culms per plot, plant height, straw weight and yield in all varieties of winter wheat tested.

Gardner et al. (1975) conducted 44 soil fertility experiments under variable soil depth and rainfall level. Evaluating the results, he classified the experiments depending on the level of yield in low, medium and high yield sites. At the medium and high yield sites he obtained yield increases in 86% of the experiments, but no grain yield increases were obtained at the low yield sites.

Leggett et al (1959) expressed that response to sulfur in eastern Washington is obtained normally when high levels of N have been applied and no sulfur utilized in recent years.

Gardner et al. (1975) also obtained responses to sulfur in a small percentage of experiments. The response to sulfur occurred mainly during seasons that produced high yields.

In eastern Washington, Leggett et al (1959) reported no effect of P on wheat yields in any of the experiments conducted.

In eastern Oregon, although Hunter et al (1961) and Gardner (1975) did not find much response to P, there is recent evidence that P fertilization may significantly affect plant growth, water uptake and the incidence of water stress particularly in late planted wheat (Glenn 1981).

5. General Aspects of Crop Water Stress.

Water stress on plants normally affects many processes and as a result produces changes in anatomy, morphology, physiology and biochemistry (Kramer 1969).

The same author has described a general picture of the plant water stress phenomenon, "photosynthesis is reduced by closure of stomata which decreases the supply of carbon dioxide, but water stress also reduces the capacity of the protoplasm to carry on photosynthesis, and reduced translocation might hinder it by accumulation of end product. The reduction in photosynthesis, decreased translocation of carbohydrate and growth regulators, and disturbance of nitrogen metabolism all add to the effects of reduced turgor in reducing growth. In turn, reduced growth reduces the photosynthetic surface, further decreasing the relative amount of carbohydrate available for growth, as compared with unstressed plants."

6. Water Stress Effects on Photosynthesis and Growth.

As plants undergo water stress the turgor pressure decreases and stomatal openings are reduced. This process is a common mechanism that plants use to maintain internal water balance. Numerous experiments have confirmed this process. Most experiments have shown that decreased CO_2 assimilation by increased stomatal resistance is the most common limiting factor of photosynthesis (Vaadia et al 1961). However, decreased protoplasmic hydration is cited as another reason that may affect photosynthesis (Vaadia et al 1961).

More recently, Slatyer (1973) investigating several crops, among them corn and wheat, found that a short period of water stress did not materially affect the photosynthesis process. He also reported that decreased CO_2 supply by stomatal closure was the primary reason for decreased photosynthesis until just before the permanent wilting point was reached, then dehydration became the major limiting factor.

Kramer (1969) pointed out that water stress exerts on photosynthesis a direct effect in various biochemical processes and indirect effects limiting the CO_2 assimilation through stomatal resistance. He also reported the opinion of some researchers who think that the most important negative effect of water stress is the reduction of photosynthesis surface. Wardlaw (1967) associated reduced photosynthesis of the flag leaf in wheat under water stress with stomatal closure, but added that more than a limitation of gaseous exchange was probably involved in the stress response.

Hsiao (1973) stated that normal cell growth is the first process affected followed by stomatal closure and then CO_2 assimilation begins to hamper photosynthesis. Thus, as the author has indicated, mild water stresses that might not affect photosynthesis may reduce development of leaf surface area. Then if for a given crop, the leaf area is critical, yield losses could be important because of the cumulative effect of mild stresses. The same author noted that in a crop like cereals where only part of the plant material (grain) is considered the main objective of production, it is very difficult to analyze the relationship between water stress and yield. He suggested that the stage of plant development at which the stress occurs and its sensitivity to stress would better explain the yield obtained. In addition he indicated that it may be important whether the photosynthate comes from many leaves or from one leaf; for example the flag leaf in wheat. This fact would affect the interaction between leaf area and water stress at different growth stages in determining yield.

In summary, mild water stresses first affect cell growth and as a consequence leaf area development. If the water stress continues, then CO_2 assimilation could inhibit photosynthesis. A higher level of water stress could lead to dehydration. However, the most important conclusion is that even small stresses can reduce the leaf area. If these minor stresses are reflected in yield losses depends on whether or not the reduced leaf area is critical for a given crop. For example, in wheat which is strongly dependent upon the flag leaf, especially during grain filling periods, it is important to determine whether accumulated mild water stresses could become decisive in determining the ultimate yield.

7. Plant Water Stress at Different Stages of Growth.

In general, the intensive growth of young tissue needs a high hydration level. This may explain why tissue with high growth levels are normally more sensitive to water stress (Slavik 1966).

Vaadia et al (1961) has shown that in some instances plant growth reduction by water stress can be recovered if water supply is restored. However, they stated, sometimes water deficits at any particular growth stage can cause irreversible damage that will be expressed by yield reduction at maturity.

Slavik (1966) reviewed several studies dealing with stage of growth and water deficit in spring wheat. Plant water stress at different growth stages may affect grain yields to a different degree:

-- water deficits during rapid leaf growth reduces the number of fertile tillers,
-- during spikelet formation the number is reduced in the spike,
-- during anthesis, the affects are on total number of grains and during grain formation the weight of individual kernels.

Fischer (1973) found that photosynthic leaf area (source) and grain per spikelet (sink) were two major factors which determine grain yield in wheat under water stress. He reported that the former is much less sensitive than the latter "which was significantly reduced by stresses not affecting leaf senescence."

It is well established that the state of growth normally most sensitive is the period about 15 days prior to anthesis. The yield component most seriously affected at that time is the grain per inflorescence (Aspinall et al 1964; Wells and Dubetz 1966; Slatyer 1969).

8. Crop Water Stress and Its Assessment.

The transpiration (demand) of all plants is affected to a certain degree by the environment, depending on the level of soil water (supply) in space and time.

Kramer (1969) described the plant water stress phenomenon as a result of excessive transpiration (demand), insufficient absorption (supply) or a combination of both. He also found that transpiration and absorption are controlled by different sets of factors. Therefore, they may often proceed at different rates. Thus, when water losses exceed water absorption, the plant water balance is upset and a water deficit develops.

Kramer (1963) has emphasized the importance of the plant water status itself rather than the relationship between soil moisture and physiological processes that not always can be related in a clear manner. Fischer (1973) found large differences between water potential of the wheat plant top and that of the bulk soil.

More recently Jackson (1982) stated, "a review of the metereological, soil and plant factors that are used to signal irrigation needs, shows that whereas meteorological and soil factors indicate when plants may be stressed, plant factors indicate when they are stressed."

Even though a factor like plant water potential is very precise for indicating plant water stress, it requires numerous samples to describe a field and is time consuming.

Plant temperature measurements have been used to provide information about the level of plant water stress. Tanner (1963) was the first investigator to use a portable infrared thermometer for this purpose and concluded that, ". . . plant temperature may be a valuable qualitative index to differences in plant water regimes. Coupled with a better understanding of transfer processes at the plant surfaces, they may serve to provide quantitative data on plant-water status."

However, a number of environmental and plant factors combine to determine leaf temperature at any given time, making its interpretation very difficult. In fact, Gates (1969) studies the problem indicating: "transpiration rate and leaf temperature are the result of the interaction of several simultaneous environmental factors interacting with a leaf to a degree determined by several plant properties." Thus, leaf temperature and the transpiration rate depends on many variables in different combinations at any given time.

Nevertheless, efforts to simplify the complexity of several variables interacting simultaneously have been made by several investigators during the past five years. The most promising area is the development of a plant water stress index system.

One of the first tasks was to determine the differences between plant temperature and crop canopy temperature. Jackson (1982) stated that there are three major means of cooling leaves cited in the literature: reradiation, convection and transpiration. He also pointed out that transpiration was seldom reported in the literature as a major means of heat transfer on a single leaf basis. However, he found that for the crop canopy, transpiration plays a key role as a cooling mechanism. Idso and Baker (1967), calculated the Bowen's ratio (ratio of sensible to latent heat exchange) for single leaves and crop canopy in soybean. They found that for individual leaves, convection was important but for canopies as a whole, transpiration was one of the major modes of heat transfer.

Jackson (1982), in a review paper concluded that: "transpirational cooling plays a major role in the energy balance" of a crop canopy and therefore in determining plant temperature. Conversely, plant canopy temperature should be related to transpiration, and hence might serve as an indicator of plant water stress." However, the measurement of the plant canopy temperature at the field level only became possible after the invention of a portable and reliable infrared thermometer. Such equipment measures infrared radiation that all objects emit with an intensity proportional to temperature. The radiation is translated to temperature based on the Stefan-Boltzman blackbody law.

The infrared thermometer stimulated further interest in developing an index to evaluate crop water stress. A simple approach to this problem was the development of the Stress-Degree-Day (SDD) concept. This index was reported by Idso, et al. (1977) and Jackson et al (1977): SDD = Temperature of the foliage - Temperature of the air. This is a daily value taken in the early afternoon (1 pm - 3 pm) because this is the time when plant water stress normally occurs (Ehrler et al., 1978b; Idso et al., 1981a). They hypothesized that, if this value is higher than zero, the plants are undergoing stress and water is needed. However, if the value is smaller than zero,there is no crop water stress. This is because well-watered plants which transpire at the potential rate generally have significantly cooler canopy temperature than those that are short of water and are unable to transpire at the potential rate. In the SDD index, it was assumed that vapor pressure, net radiation and wind would be expressed in the canopy temperature.

Walker and Hatfield (1979) tested the SDD concept working with red kidney beans planted on four different dates and five different irrigation treatments in each date. They plotted the SDD summation of daily value from flowering to maturity against total amount of water used. They found a negative straight line relationship between these parameters (the less the water available for transpiration, the higher the SDD summation value). This fact demonstrated the direct relationship between transpiration and canopy temperature. The SDD concept worked reasonably well in several other experiments (Hatfield et al., 1978; Idso et al., 1979). However, some other studies have found that SDD is significantly affected by air vapor pressure deficit (Idso, 1982; Bonanno, 1982).

The team of scientists who developed the SDD concept admitted the limitation of the model and continued to further improve it.

Ehrler (1973) in field experiments with well watered cotton, measured the leaf temperature using wire thermocouples. He was the first who plotted the leaf-air temperature differential against the air vapor pressure deficit, finding a linear relationship between them, for a well irrigated cotton crop.

Idso et al., (1981a) using this concept, developed the Crop Water Stress Index (CWSI) which is essentially a SDD index adjusted for air vapor pressure deficit variability. They found, working with well watered alfalfa, that the linear relationship first discovered by Ehrler (1973), holds throughout most of the hours during the day, despite the variation in radiation. This kind of biological constant was used as a lower limit (see Figure 1) postulated as a potential transpiration baseline (non-water-stressed baseline) when the crop shows no water stress. The upper limit (maximum stress) is reached when transpiration ceases. This is theoretically estimated and seems to show agreement with actual data obtained in senescent wheat (non-transpiring plants) (Idso, et al., 1981c). This estimation is fully explained in Idso et al., (1981a) and Idso et al. (1981b).

In four different environments (Minnesota, Kansas, Nebraska and Arizona), Idso et al. (1981b), working in well irrigated alfalfa field experiments, found that all the data from the locations fit a single relationship in the format previously explained.

Knowing the linear relationship (non-water-stressed baseline) for a given crop, the CWSI can be calculated for most of the daylight period and under very different environments.

9. Crop Water Stress Index (Graphical representation)

In Figure 1, the non-water-stressed baseline is considered the lower limit and the maximum stress line the upper limit. The CWSI for a given crop at P, is defined as the ratio of the vertical distance above the non-water stressed baseline, (AP) not transpiring at the potential rate due to some level of water deficit, to the total possible distance that it could potentially travel (AB). Then CWSI = AP/AB (Idso et al., 1981a).

Idso (1982) has further studied this non-water-stressed baseline for 26 different species indicating that each one has its own unique linear relationship with the exception of one aquatic plant that has a curvilinear relationship. The interesting thing from our point of view is that the baselines of some crops may shift significantly as they change from vegetative to reproductive stage (Figure 2). That is the situation in cereals like barley and wheat suggesting that changes in canopy structure cause this behavior.

In these types of crops, the non-water-stress relationship will have to be adjusted to current growth and development stage in order to use the CWSI correctly.

In conclusion, it appears that the invention of the portable infrared thermometer and the development of the CWSI makes it possible to quantify crop water stress at the field level. An accurate measurement of the daily stresses that the crop is undergoing during the entire growing season should clarify and improve the understanding of the relationship between crop water stress and yield.

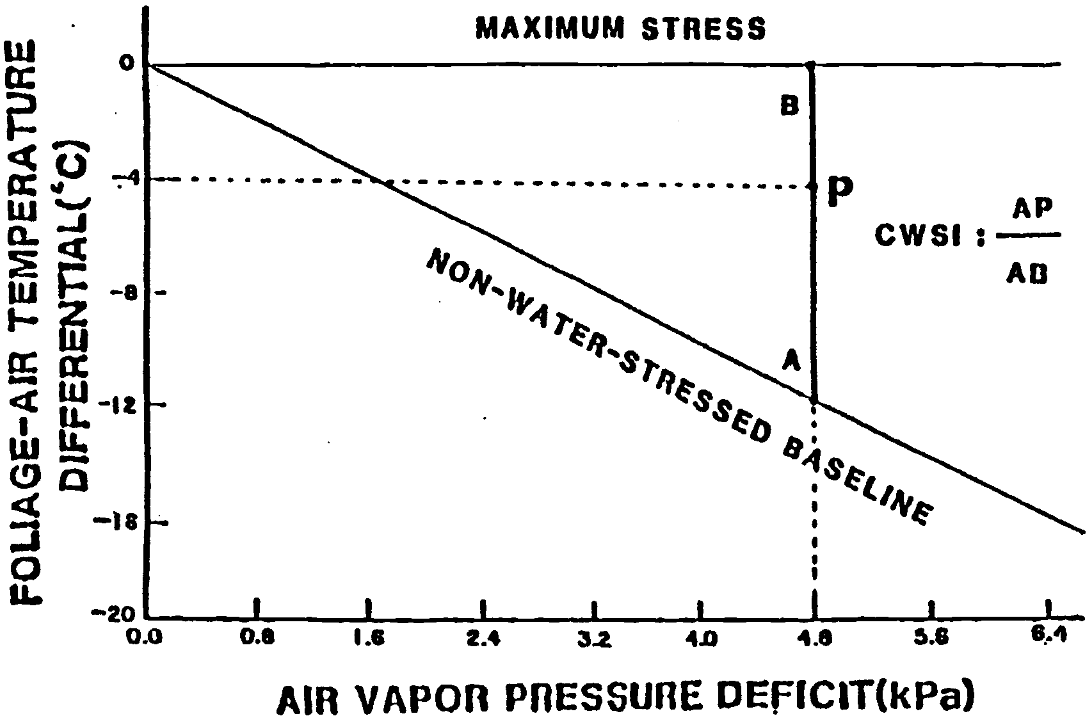
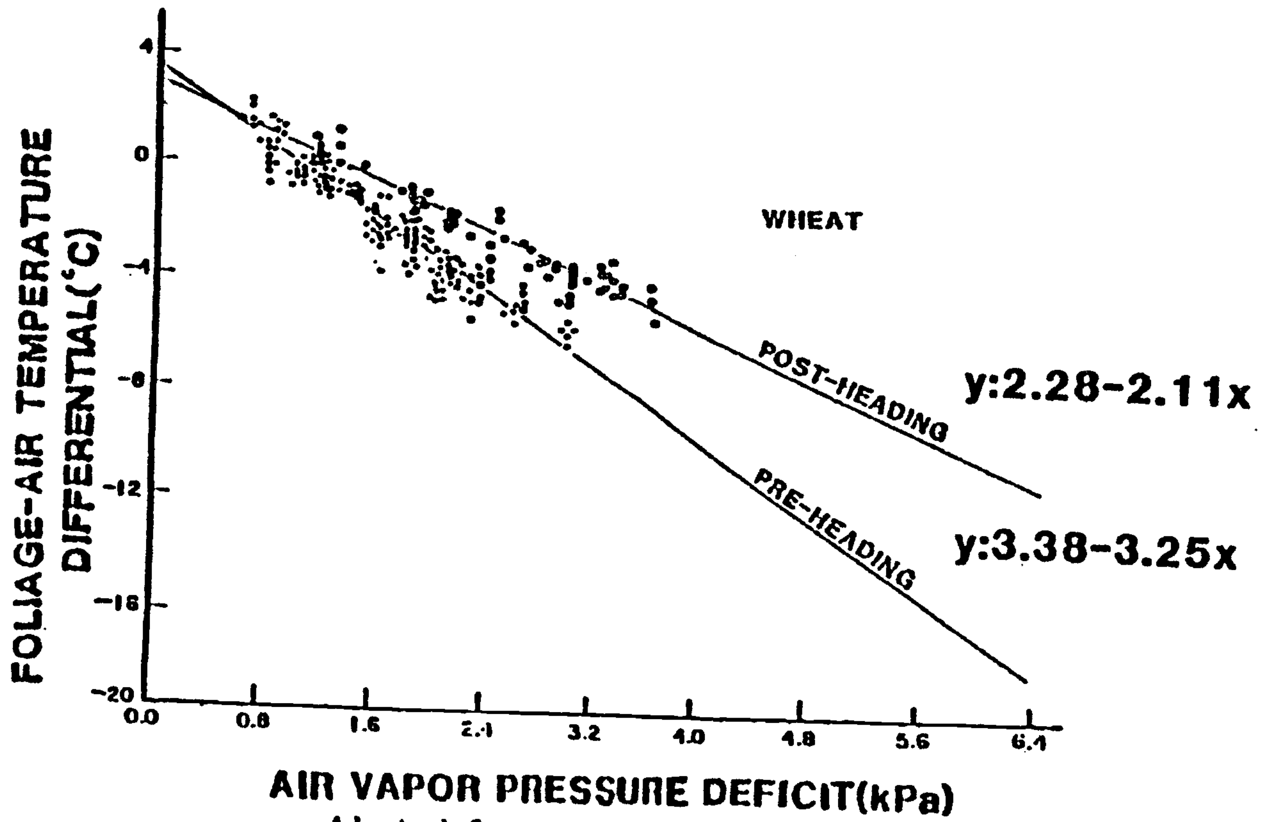


Figure 1: Graphical representation of the CWSI. Given a foliage-air temperature differential of -4^{o}C and an air vapor pressure deficit of 4.8 kPa, then the CWSI at P is the ratio between the distance travelled above the non-water-stressed baseline (AP) and the total distance that P could theoretically travel between lower and upper limit (AB).



Adapted from Idso (1982)

Figure 2: The non-water-stressed baseline for wheat during the pre-heading and post-heading stage of growth.

MATERIALS AND METHODS

Replicated field trials on soft, white winter wheat (*Triticum aestivum* c.v. Stephens) were conducted at the Sherman Experiment Station, Moro, Oregon during the 1981-1982 and 1982-1983 crop seasons. All experiments were on a relatively deep, Walla Walla silt loam soil series (coarse-silty, mixed, mesic Typic Haploxeroll).

This study consisted of two experiments. All trials received a uniform application of sulphur at the rate of at least 25 kgS/ha in the form of ammonium sulphate or potassium sulphate (on the 0-nitrogen treatments) to insure that this fertilizer element was in adequate supply and not a variable in the experiments.

1. Nitrogen x Phosphorus x Date of Planting Field Experiment (NPD field experiment)

This trial was arranged in a split-plot design with four replications. The main plot treatment was date of planting: early (mid-September) and late (mid-November). These are called Date 1 (D1) and Date 2 (D2), respectively. The subplots consisted of nitrogen treatments at rates of 0, 60 and 80 kg N/ha and phosphorous at rates of 0 and 44 kg P/ha factorially arranged within each date of planting:

Main plot size	36.6 m x 6.1 m = 223 square meters
Sub plot size	6.1 m x 6.1 m = 37.16 square meters

Subplot number	Subplot treatment	
1 *	no N	no P
2 *	no N	44 kg P/ha
3	60 kg N/ha	no P
4 *	80 kg N/ha	no P
5	60 kg N/ha	44 kg P/ha
6 *	80 kg N/ha	44 kg P/ha

The fertilizers used were ammonium sulphate (20.5% N and 23.4% S) and triple super phosphate (19.35% P).

The fertilizers were broadcast just before planting and incorporated within the upper 15 cm layer of soil by the deep furrow planter. The planting rate used was about 230 viable seeds per square meter. Each subplot consisted of 18 rows 6.1 meters long with 30.5 cm between rows.

In treatment numbers 1, 2, 4 and 6 (*), plant samples and soil moisture readings as well as canopy temperature measurements were taken. Plant samples and soil moisture measurements were taken from one half of each subplot, while the other half was reserved for crop canopy readings and grain yield determinations.

When plant growth resumed in early spring, samples were cut at the soil surface level from one meter of row length (0.3 square meter) about every 15 days for determination of the following: tiller and spike number, total dry weight of sample, dry weight of stems, leaves and spikes. The plant samples were oven-dried at 105°C for 24 hours.

Soil moisture readings were made using a neutron-moisture probe (Campbell Pacific Nuclear - model 503 hydroprobe) about every 15 days which coincided with the plant sample period. The sampling period was from early spring to harvest. The soil moisture sampling depths were 7.5, 15, 30, 60, 90, 120, 150, 180, 210 and 240 cm during the 1981-82 season in all subplots. In 1982-83, some plots had restricting layers around 100-150 cm which limited measurements to that depth. The area around each access tube was left undisturbed so that moisture readings would reflect the actual water uptake of the plants. The access tubes were installed in early March and early April in 1981-82 and 1982-83 respectively.

The canopy-air temperature differential and relative humidity (R.H.) were taken with a portable infrared thermometer (Everest 110) which has 0.1°C resolution with ± 0.5°C accuracy and a sling psychrometer, respectively. Readings were taken on a daily basis at 1 to 3 PM during March 27-July 21 in 1982, and April 12-July 19 in 1983. The readings were begun for each planting date whenever there was enough foliage development to avoid upward soil radiation. During the first growing season only one reading was taken in each plot with direction from south to north. In the second growing season two measurements were made at each plot (south-north and north-south) and averaged. The instrument was always hand-held at 1 m above the crop at an oblique angle of about 30° in order to measure only the foliage temperature and to avoid the underlying soil radiation.

Canopy temperature, canopy-air temperature differential and R.H. were used to calculate CWSI on a daily basis for all the plots measured. CWSI was computed using 2 different equations depending upon whether the crop was in pre-heading or post-heading stage of growth (see figure 2) (Idso, 1982).

Heading date was determined for each treatment by measuring head extension in a 10 spikes sample from each plot, averaging the total 40 determinations for each treatment.

At maturity, grain yield was calculated by harvesting 6 square meters in each plot. Moisture content of the wheat grain was determined at harvest by drying a pooled sample from all treatments following standard procedures (105°C temperature - 24 hours).

Specific weight was measured using a Fairbanks scale. An electronic counter was used to estimate 1000 grain weight. Soft wheat grain protein content was analyzed using a Technicon 400 infra-analyzer.

At harvest, the 1 meter spike samples were threshed and weighed to calculate grain weight per spike and grain number per spike.

2. Nitrogen Field Experiment (N field experiment)

This experiment was planted in a randomized block design with four replications. The treatments were different nitrogen levels: 0 (control), 20, 40, 60, 80 and 100 kg N/ha. The treatments with 40 and 80 kg N/ha were also broadcast in a split application (50% at planting and 50% at tillering).

	Treatment kg of N/ha	
Treatment number	at planting	at tillering
1 (control)*	0	0
2	20	0
3 *	40	0
4	60	0
5 *	80	0
6	100	0
7	20	20
8	40	40

In treatments 1, 3 and 5 (*), soil moisture readings and canopy-air temperature were taken in the same way and on the same schedule as for the N x P x Date of Planting, field experiment. The date of planting was mid September for both growing seasons. Other factors remaining constant as in the NPD experiments The plot size was 3 x 6 = 18 square meters, harvesting about 6 square meters.

Grain moisture content, test weight, 1000 grain weight and soft white wheat grain protein were also analyzed in the same way.

RESULTS AND DISCUSSION

1. General Discussion

Three factors that directly determine crop water stress, are soil water availability supplied by rainfall, maximum air temperature and relative humidity (RH).

During the 3-year period (1980-1983) of this study, the precipitation (Figure 3) was generally above the long-term average. Figure 4 shows the total amount of precipitation from September to August during the following periods: 1980-81, 1981-82, 1982-83 and the long-term average for 71 years at the Sherman Agr, Exp. Sta., Moro, Oregon. During these years the annual rainfall were 6%, 27%, and 52% respectively above the 71-year average.

During the crop period when most of the data were collected (March-July), there was little difference in the maximum temperature of the air (daily values, monthly, averaged) as compared with the long-term average during the 1951-80 period (Table 1)(NOAA 1982). However, it is clear that June and July were cooler than the 29 year average in 1983.

The minimum relative humidity, a third component used to determine crop water stress, was substantially higher during both years compared with the long-term average (1963-74)(Table 2).

Therefore, these climatic conditions were generally favorable for wheat yields and less than normal crop water stress was expected.

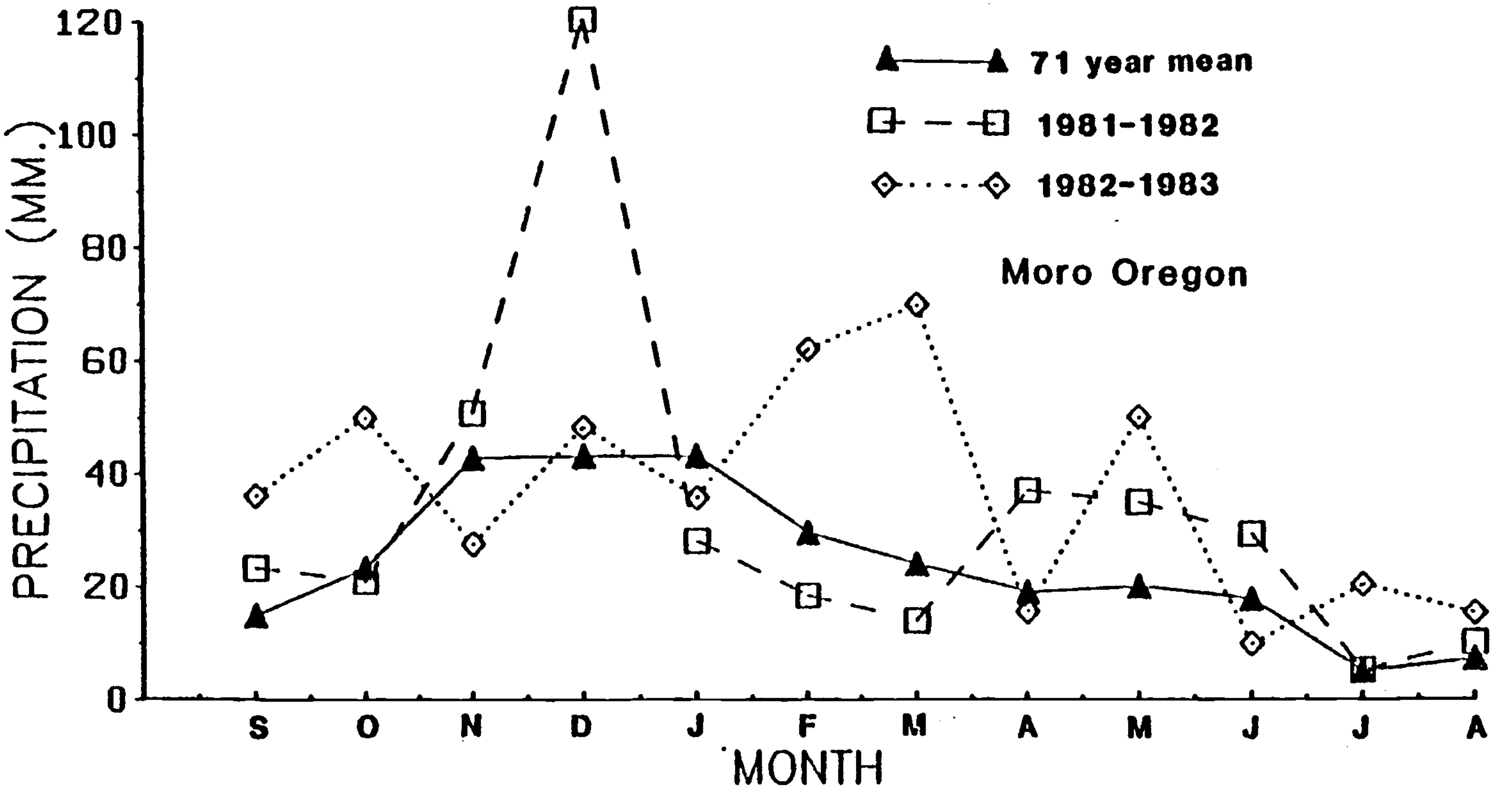


Figure 3: Total monthly precipitation during 1981-1982, 1982-1983 and the 71-year mean.

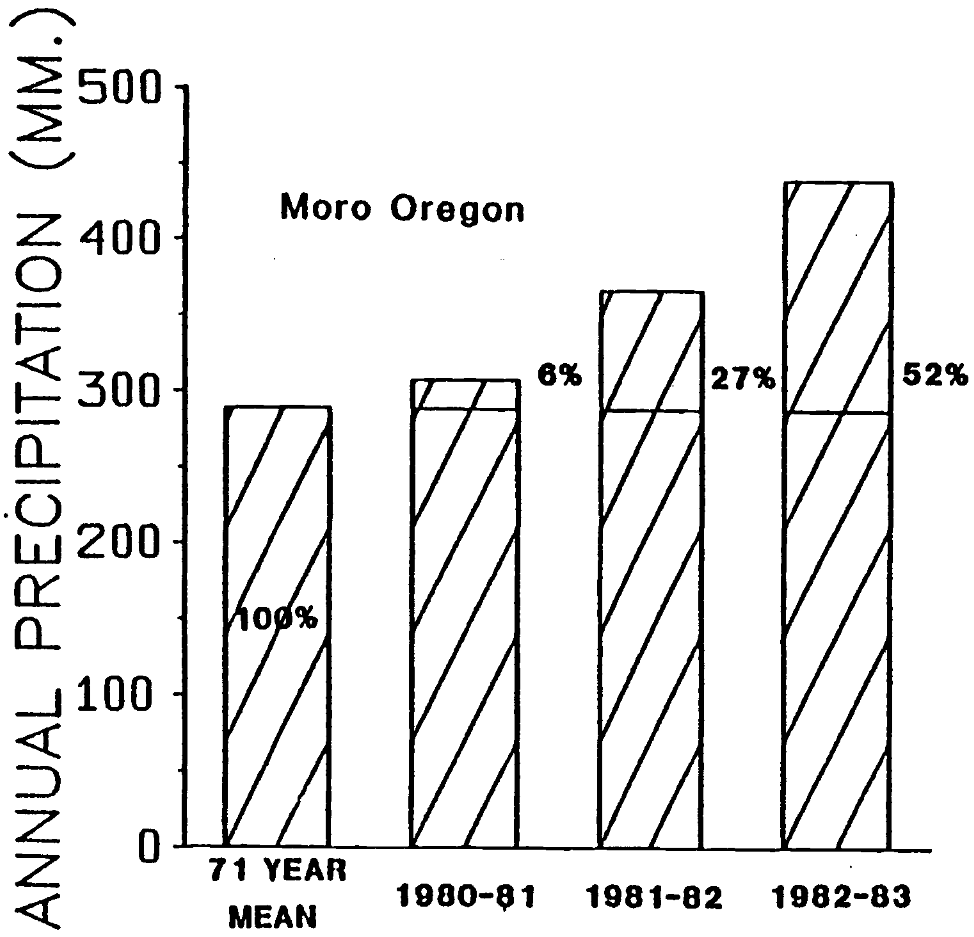


Figure 4: Seasonal precipitation (12 month, September-August) showing the increase (%) above the 71 year average.

Table 1: Monthly mean of maximum daily temperature (oC) during spring growth period (March-July).

	March	April	May	June	July
1951-1980 (29 yr average)	10.1	14.2	18.9	23.4	28.4
1982	10.3	12.4	18.2	24.4	26.2
1983	11.1	13.8	19.9	21.4	17.7

Table 2: Monthly mean of minimum relative humidity (RH)(%) during spring growth period (March-July).

	March	April	May	June	July
1963-1974 (12 yr average)	51.2	48.8	44.5	43.9	39.6
1982	62.0	55.4	49.3	54.8	42.6
1983	--	64.3	52.0	53.1	55.3

In addition, the response to nitrogen fertilization was greater than usually experienced (Hunter et al 1961; Gardner 1975).

As a result of these favorable climatic conditions, most of the treatment variation in this study can be explained in terms of N vs. no N response.

Response to phosphorus subtreatment was visible during both years in the seedling stage as expressed in plant vigor, early in the spring but disappeared completely later in the season.

The soil P determined from samples taken in untreated plots in the experimental sites, averaged 13.5 ppm in 1981 and 15.2 in 1983 (before planting time and early spring, respectively). These values are close to the critical point where some response to P fertilization should occur (Gardner et al 1980; Pumphrey and Rasmussen 1982). The method of P application, i.e. broadcast and seeded through with a deep furrow drill, may have had an effect on the availability of this plant nutrient. However, the rate used was quite high (44 kg P/ha) and therefore should have provided an adequate supply of this nutrient if it was actually deficient in these soils. However, under normal or drier weather conditions a significant response to P may have occured (Arnon 1975; Glenn 1981b).

In the 1982 Nitrogen X Phosphorus X Date of planting (NPD) experiment, very noticeable differences were observed during late tillering and early heading between N subtreatments, especially in Date 1 (better development in subtreatments with N). After heading, these differences were reduced or disappeared. In 1983, growth differences between subtreatments with N vs. no N were even greater and remained until the end of the season (harvest time). It is very well established that N can produce a tremendous effect in promoting vigorous plant growth (Arnon 1972; Olson and Kurtz 1982).

The differences in growth between dates of planting was greater during 1983 than in 1982. The Date 1 of planting had consistently better development than Date 2. The larger difference in 1983 was not because higher rainfall in this year favored Date 1 over Date 2 but rather a crusted surface in Date 2 resulted in very poor stand establishment.

In the trial plots of the 1981-82 season a rather severe infestation of weedy grasses, primarily Bromus tectorum, may have had a significant effect on the trial results. Despite efforts to control the grass using the herbicide mixture of metribuzin + 2,4-D + bromoxynil, and attempts to handweed the plots, there was incomplete control of the weedy grasses. This was more evident in the subtreatments with added nitrogen than in the other plots (Table 3). Even with the weeds, highly significant differences in grain yield were recorded between the nitrogen and no nitrogen subtreatments. The results would probably have been even greater in the absence of weedy grasses. In the 1983 plots weed control was adequate and presented no problem in the trial.

2. Statistical Analysis

For the experimental design used in the NPD experiment "the preferred way to analyze is to partition the treatment sum of squares into the components associated with the main effect contrast and the two and three factor interaction contrast for the three factors" (Nitrogen, Phosphorus, and Date of planting)(Peterson,1977). However, the only interaction that occurred in these trials was the planting date X nitrogen fertilizer level for the grain protein content factor. This was true for both the 1982 and 1983 seasons. Therefore in the NPD experiment all of the other data were arranged in one way tables, using only the F test because the comparison was between two means.

Table 3: Dry matter yield of weedy grasses (*Bromus tectorum*) in the NPD field experiment, 1982. (Data represents average of 6 samples in each subtreatment of Date 1).

Subtreatment	Dry matter yield of weedy grasses (g/0.3 m2)
Control OP-ON	9.9
P	8.7
N	52.2
P + N	39.9

3. Crop Water Uptake

It was not the objective of this study to measure actual crop water uptake but only to measure the differences among treatments. Thus the rain that occurred between the period of readings, the water losses by soil evaporation and deep underground drainage were not considered. In other words, crop water uptake was computed simply by differences between readings. These calculations are presented at two periods of time:

Pre-heading (Pre-H): from the beginning of the readings (March 27 in 1982, April 24 in 1983) until heading.

Post-heading (Post-H): from heading until harvest.

The beginning of the readings was delayed in 1983 due to heavy rains that made it impossible to install the soil access tubes at the same date as in 1982.

In the NPD experiments the total water uptake during the period studied (March 27-July 22 in 1982 and April 26-July 21 in 1983) throughout the soil profile measured (0-240 cm in 1982 and 0-120 in 1983) was increased (P=0.01) by the N application in both years (last column in Table 4). These results are in agreement with the data reported by several authors (Koheler 1960; Ramig and Rhoades 1963; Kmoch 1957). The soil water measurements during both seasons clearly show that water uptake occurs mainly in the upper soil layer (0-90 cm) in the Pre-H period and from the deeper soil layers (90-180 cm) in the Post-H period (Table 4 and Figure 9). These results are in agreement with the observations previously reported by Hurd and Spratt (1975).

The same results were measured in the Nitrogen (N) field experiment in 1983 but not during 1982 (Table 5). During this year, no significant total crop water uptake difference was observed between treatments (0, 40, and 80 kg N/ha). However highly significant differences were detected between the treatments in Pre-H in the deeper soil layers.

In summary, nitrogen fertilization at a rate of 80 kg/ha increased water uptake by 23-45 mm compared to control. These are similar to the results of Ramig and Rhoades (1963) in Nebraska.

4. Crop Water Stress Index (CWSI)

The CWSI was computed following the procedures outlined in the materials and methods section. These daily plot values were arranged by two periods of crop growth, Pre-H and Post-H (Table 6 and 7), or by period of plant sampling (about every 15 days)(Figure 5-8).

Table 4: Crop water uptake(mm) in the NPD field experiment during pre-heading (Pre-H) and post-heading (Post-H) at different depths in the soil profile (1982-1983 seasons).

1982

Period	Pre-H	Pre-H	Pre-H	Post-H	Post-H	Post-H	TS	TS	TS	Pre-H	Post-H	TS
Depth(cm)	0-90	90-180	180-240	0-90	90-180	180-240	0-90	90-180	180-240	0-240	0-240	0-240
Nitrogen (kg/ha)												
0	51.19	32.56	15.56	28.69	55.81	24.00	79.88	88.38	39.56	99.31	108.58	207.81
80	64.63	48.88	20.37	20.68	62.13	28.75	85.31	111.00	49.13	133.88	111.56	245.44
F	35.55**	35.01**	3.46ns	14.13**	3.55ns	4.92*	10.92**	34.43**	7.19*	36.09**	0.38ns	46.35**
se(mean)	1.59	1.95	1.83	1.50	2.37	1.51	1.16	2.73	2.52	4.07	3.52	3.91

1983

Period	Pre-H	Pre-H	Post-H	Post-H	TS	TS	Pre-H	Post-H	TS
Depth(cm)	0-60	60-120	0-60	60-120	0-60	60-120	0-120	0-120	0-120
Nitrogen (kg/ha)									
0	21.13	15.31	21.00	36.38	42.13	51.69	36.44	57.38	93.81
80	30.06	31.75	21.19	55.75	51.25	87.5	61.81	76.94	138.75
F	23.05*	76.81**	0.00ns	21.99**	3.65ns	83.73**	78.10**	9.50**	41.18**
se(mean)	1.32	1.33	3.04	2.92	3.38	2.77	2.03	4.49	4.95

Total period scanned (TS): Pre-H + Post-H (March 27 - July 22 in 1982) (April 26 -July 21 in 1983)

* Significantly different at 5% level.

** Significantly different at 1% level.

ns Not significantly different.

Table 5. Crop water uptake(mm) in the N field experiment during the heading (Pre-H) and post heading (Post-H) at different depths in the soil profile (1982-1983 season).

1982

Period	Pre-H	Pre-H	Post-H	Post-H	Pre-H	Post-H	TS
Depth	0-90	90-180	0-90	90-180	0-180	0-180	0-180
Treatment (kg N/ha)							
0	61.50	41.50	22.75	40.25	103.00	63.00	166.00
40	70.00	45.75	18.75	40.00	115.75	58.75	174.50
80	73.00	65.50	14.00	45.00	138.50	59.00	197.50
F	4.28ns	10.90**	6.35*	0.19ns	8.08*	0.13ns	3.37ns
se(mean)	2.88	3.88	1.74	6.54	6.33	6.63	8.87
LSD 0.05	-	13.42	6.01	-	21.90	-	-

1983

Period	Pre-H	Pre-H	Post-H	Post-H	Pre-H	Post-H	TS
Depth(cm)	0-30	30-90	0-30	30-90	0-90	0-90	0-90
Treatment (kg N/ha)							
0	17.50	6.25	27.00	20.75	23.75	47.75	71.50
40	27.00	16.00	30.75	26.50	43.00	57.25	100.25
80	37.00	20.50	18.50	18.25	57.50	36.75	94.25
F	42.79**	10.90**	5.71*	3.40ns	31.06**	7.44*	10.96**
se(mean)	1.49	2.21	2.63	2.29	3.04	3.76	4.58
LSD 0.05	5.16	7.64	9.09	--	10.51	13.01	15.86

Total period scanned (TS): Pre-H + Post-H (March 27-July 22 in 1982) (April 26-July 21 in 1983)

* Significantly different at 5% level.

** Significantly different at 1% level.

ns Not significantly different

a. NPD field experiments

The cumulative CWSI, Pre-H and Post-H, were lower (P=0.01) in both periods for those subtreatments with N as compared with those having no N, during 1982 (Table 6).

In 1983, although there was a significantly lower total value (P=0.05), again for these treaments with N, there was a difference during Post-H (P=0.05), but not at the Pre-H period. However, due to very favorable climatic conditions during Pre-H, there was no plant water stress (no N subtreatment: 0.96; N subtreatment: 0.66). Since these values, represent approximately 40 days of reading, these daily CWSI means would be about 0.024 and 0.017 respectively (CWSI daily range is between 0 and 1). Jackson (1982) reported that a daily CWSI of 0.3 is the level where some crop growth reduction is imminent to occur and irrigation should be given when daily CWSI is within the range of 0.3-0.5.

Considering the cumulative CWSI by date of plant sampling, here is a significant difference at 1% level between no N vs. with N subtreatments, during the period from May 18 until June 15 (138 and 166 Julian days: JD)(Figure 5). This corresponds to a critical period (heading time) for both dates of planting and may contribute to the higher yield in the N subtreatments.

It is well known that the 15 days previous to anthesis are very important determinants of yields (Aspinall 1964; Wells and Dubetz 1966; Slatyer 1969).

Table 6: Cumulative CWSI in the NPD field experiment during pre-heading (Pre-H), post-heading (Post-H) and the total period (1982-1983 seasons).

1982

Period	Pre-H	Post-H	Total
Nitrogen (kg/ha)			
0	5.06	14.56	19.62
80	3.16	12.50	15.66
F	20.82**	12.12**	23.72**
se(mean)	0.29	0.35	0.57

1983

Period	Pre-H	Post-H	Total
Nitrogen (kg/ha)			
0	0.96	7.10	8.06
80	0.66	5.42	6.08
F	1.92ns	4.42*	5.21*
se(mean)	0.16	0.56	0.62

* Significantly different at 5% level
** Significantly different at 1% level
ns Not significantly different

Table 7. Cumulative CWSI in the N field experiment during pre-heading(Pre-H), post-heading (Post-H), and total (1982-1983 season).

1982

Period	Pre-H	Post-H	Total
Treatments (kg N/ha)			
0	4.30	20.68	24.98
40	3.22	18.43	21.65
80	2.60	19.48	22.08
F	2.01ns	0.47ns	0.71ns
se(mean)	0.61	1.64	2.16
LSD	-	-	-

1983

Period	Pre-H	Post-H	Total
Treatment (kg N/ha)			
0	0.73	14.87	15.60
40	0.59	7.21	7.80
80	0.18	5.52	5.70
F	1.01ns	7.70*	6.63*
se(mean)	0.29	1.79	3.04
LSD 0.05	-	6.21	10.51

* Significantly different at 5% level
** Significantly different at 1% level
ns Not significantly different

After the 181 JD, both groups of subtreatments show a very sharp increase in CWSI with no significant differences between them. Apparently both groups of subtreatments were beginning to show water deficiencies.

The same data collected for calculation of the CWSI in the 1983 trial shows the same trend throughout the study period. However, there were no significant differences between any of the treatments in the six time periods considered (Figure 6).

b. N field experiment

In the nitrogen field experiment, the readings of CWSI were made for 3 treatments (0, 40, and 80 kg N/ha). There was no difference among these treatments during 1982 when grouped by Pre-H and Post-H periods (Table 7). This is in agreement with the data displayed in Figure 7, with the cumulative CWSI by period of sampling. The three treatments appear to be equal. Thus the CWSI was able only to detect the development of the plant-water stress for overall growth period (peaks on May 7 = 127 JD and on June 30 = 181 JD), but failed to determine differences among treatments, possibly due to residual fertility from the previous crop.

In 1983 (Table 7), it is evident that there was a difference between control (0 kg N/ha) and the other treatments (40 and 80 kg N/ha). There was a difference at the post-H period (P=0.05). In Figure 8, the development of the CWSI is shown through the sampling dates, which is in agreement with the results in Table 7.

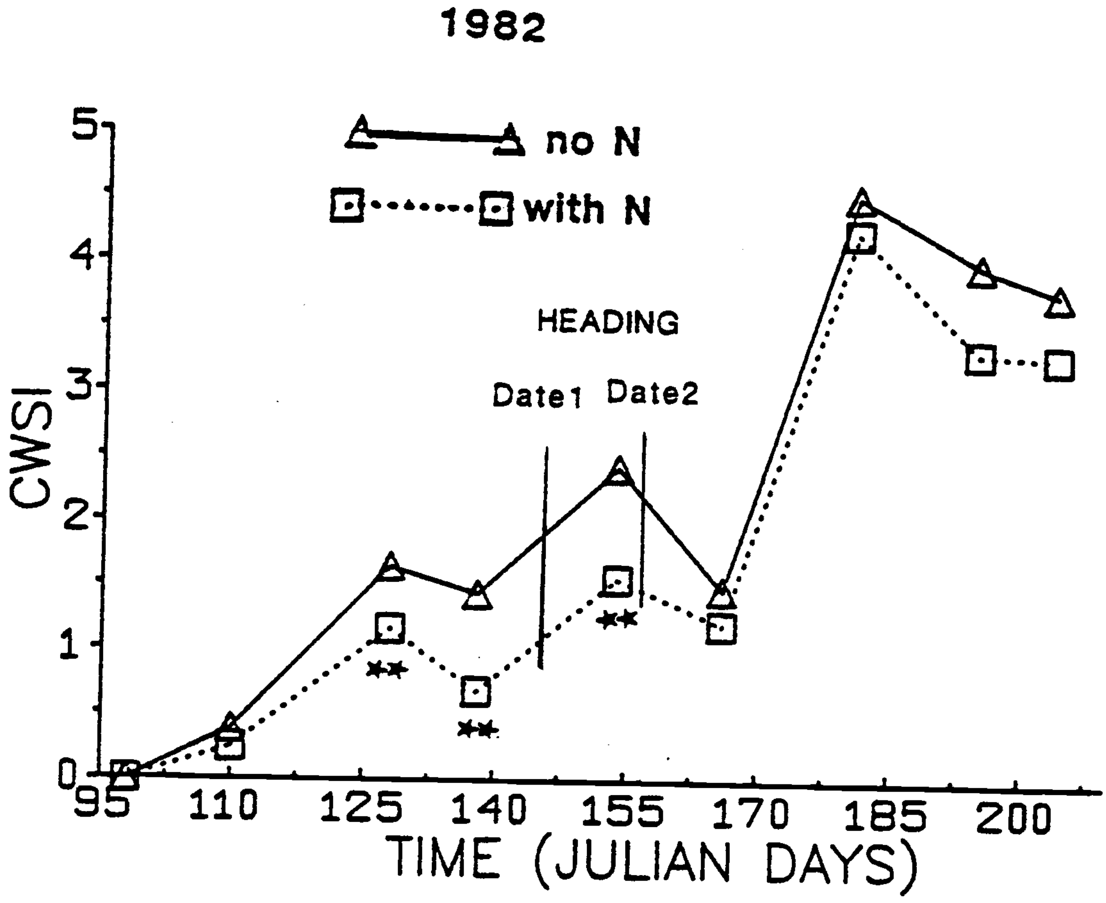


Figure 5: Cumulative CWSI by sampling period in the NPD field experiment during 1982 season.
(** Significance between means at 1% level.)

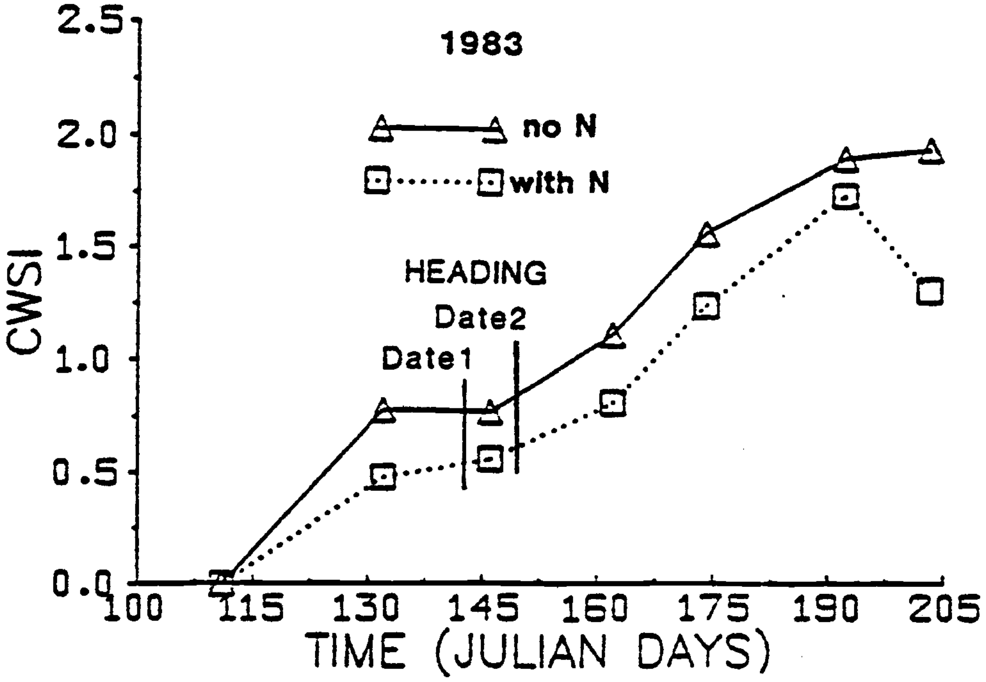


Figure 6: Cumulative CWSI by sampling period in the NPD field experiment during the 1983 season.

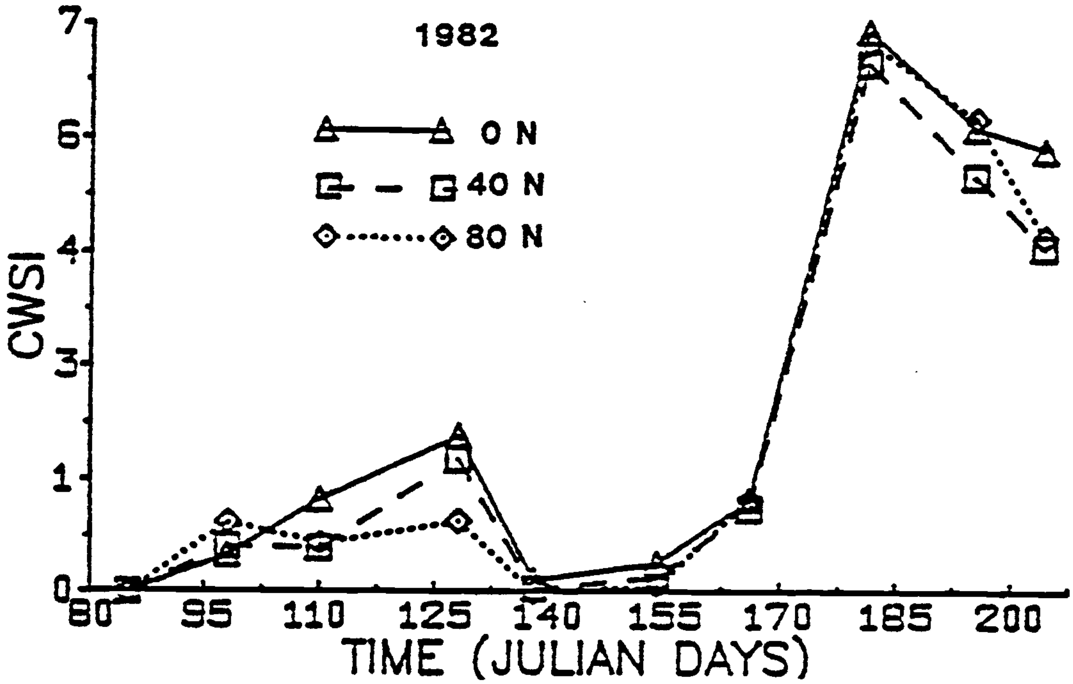


Figure 7: Cumulative CWSI by sampling period in the N field experiment during the 1982 season. The treatments are 0, 40, and 80 kg N/ha.

c. CWSI (overall results from all trials)

The results obtained in 1982 and 1983 (Figures 5-6 and Figures 7-8), may not be directly comparable because the numbers of days between sampling are not exactly the same. However, it is very clear that the CWSI level was substantially lower in 1983 reflecting the higher level and duration of precipitation during the spring growth period (Figure 3).

5. Crop Water Uptake and CWSI

Attempts to correlate a low level of CWSI with crop water uptake were not successful because at times the atmospheric water demand was low. CWSI was therefore also low. Perhaps there are other factors involved in this relationship such as increased efficiency in water used due to better nutritional status (Koehler 1960; Viets 1972). Substantial increases in WUE were obtained due to N, especially in 1983, where the precipitation was higher (Table 8). However, a clear difference in CWSI shown in Figure 5, was obtained during May 18 to June 15 (138-166 JD) which could be related with a higher water uptake in the treatments with N (Table 4).

The crop water uptake at 0-90 cm and 90-180cm depth and CWSI for no N and with N subtreatments in Date 1 during 1982 are presented in Figure 9. Both groups of subtreatments shows a peak of CWSI (125-130 JD) probably related with lower precipitation than normal during January-March followed by above average rainfall during April (Figure 3). During grain filling period there is another CWSI peak greater than the previous one. This seems to be

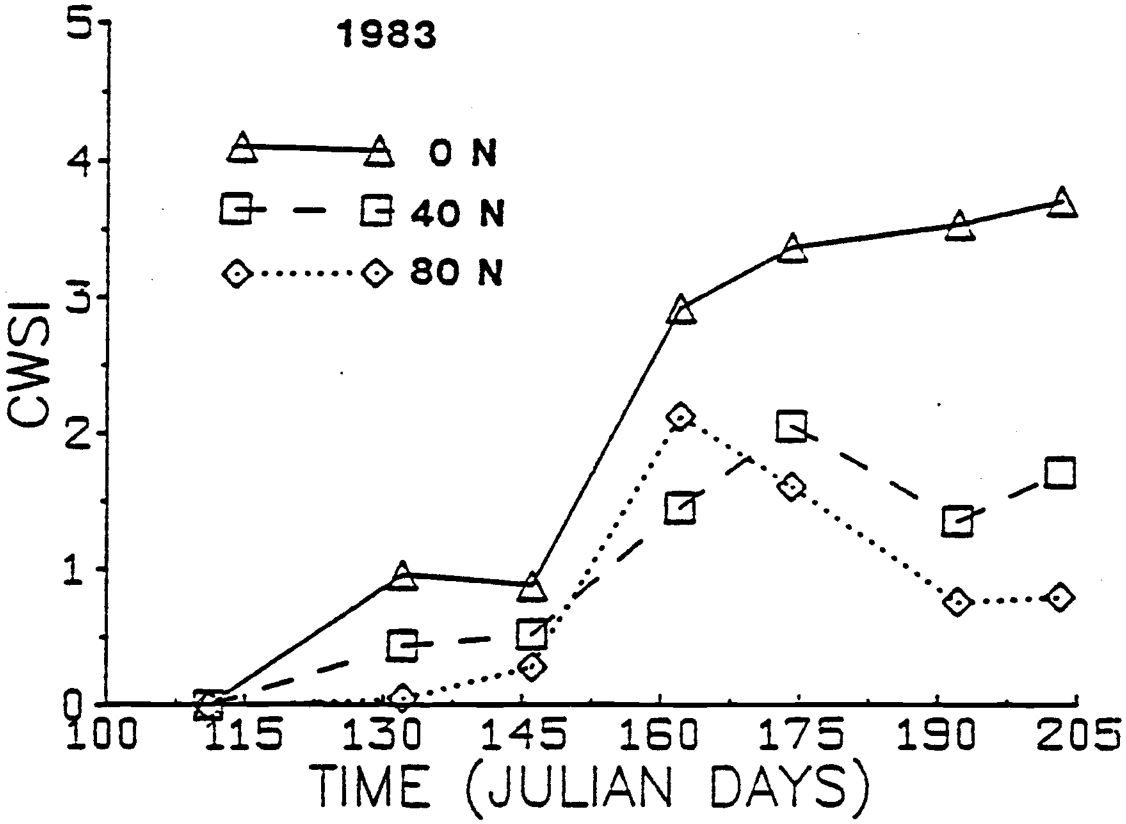


Figure 8: Cumulative CWSI by sampling period in the N field experiment during the 1983 season. The treatments are 0, 40, and 80 kg N/ha.

related with drying out of the 0-90 cm soil layer. Thus at this time not only the water demand was higher (higher air temperature, lower relative humidity) but also the crop had to extract water from a deeper soil layer. In 1983, there was a common difference during the entire period surveyed, in the CWSI level for the same contrast of treatments (Figure 6). However, this difference in CWSI is not significant, but the water uptake is higher in these treatments with N (Table 4). The high level of soil water and climatic conditions (lower temperature, higher relative humidity) was not conducive for crop water stress. Furthermore the greater vegetative development (Figure 14) in the N subtreatments produced higher water use than in the no N subtreatments.

In the N experiment in 1982, there are no differences in CWSI level among treatments (Figure 7 and Table 7) but there was a higher water uptake at Pre-H in the deeper layer of the soil profile (Table 5). Again it might be related with the greater vegetative growth in the treatment with 80 kg N/ha. This treatment may have had better root development and a higher water demand to maintain.

6. Dry Matter Production and Yield

The data in Figure 10 presents the total dry matter production as a mean of all treatments and subtreatments in each year (1982-1983). Attempts to relate the final level of dry matter production (last date of sampling) and yield were not successful. This may be

Table 8. WUE (kg of grain per ha/mm of precipitation in 24 months) in the NPD and N field experiments (1982 and 1983 seasons).

NPD field experiment

Nitrogen (kg/ha)	1982	1983
0	4.32	3.61
80	5.19	6.24
F	25.79**	44.76**
se (mean)	0.12	0.28
WUE increase (%) due to nitrogen	16.8	42.1

N field experiment

Rate of nitrogen (kg N/ha)	1982	1983
0	4.04	2.76
20	4.91	3.33
40	5.50	4.22
60	5.97	4.55
80	6.07	4.90
100	6.26	5.32
20 + 20	5.48	4.36
40 + 40	5.67	4.81
F	5.52**	10.91**
se (mean)	0.31	0.26
LSD 0.05	0.90	0.76
WUE increase between 0 and 80 kg N/ha (%)	33.4	43.7

** Significantly different at 1% level
* Significantly different at 5% level
ns Not significantly different.

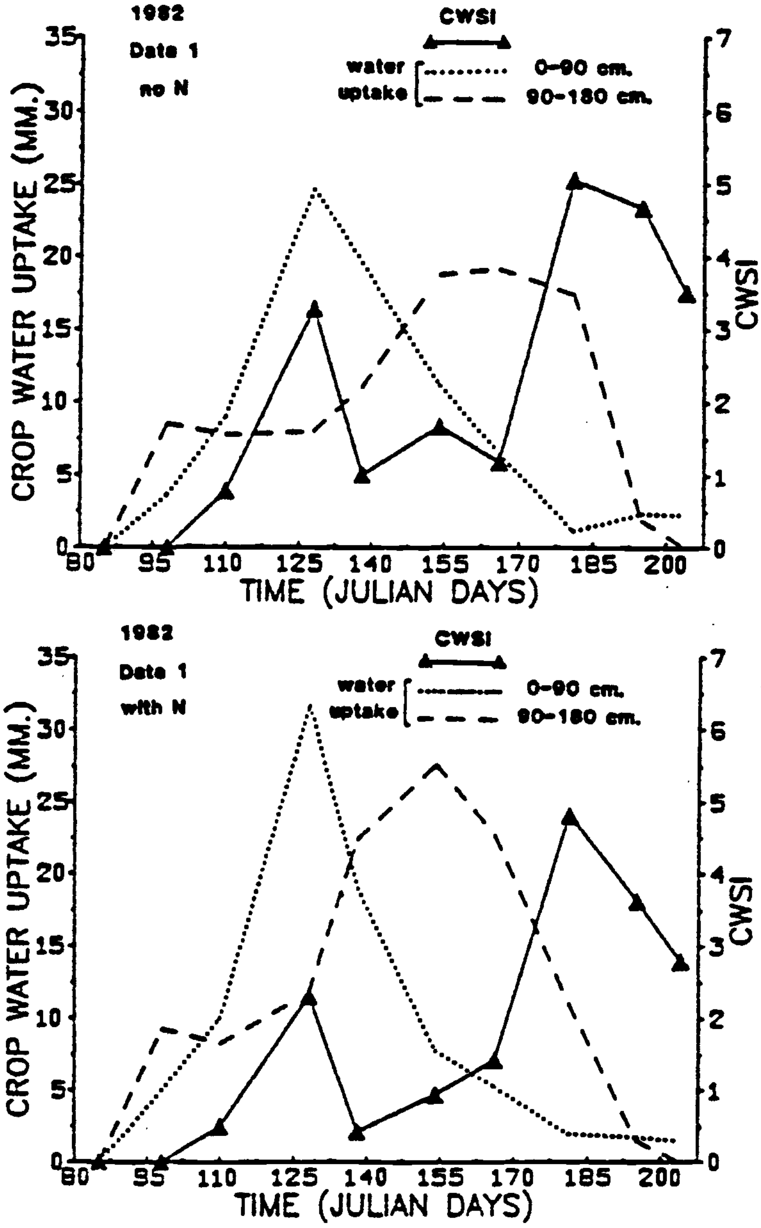


Figure 9: Crop water uptake from 0-90 and 90-180 cm soil depths and CWSI for no N and with N subtreatments in planting Date 1, 1982 season.

due to some error or environmental variability involved in the sampling. In both years, the rate of growth appeared to decrease on the last three dates of sampling. This is a normal behavior for dry matter increase over time. An improved relationship between dry matter production and grain yield is shown in Figure 11. These data are a result of the average of the last three sampling dates which represents a time period of about 30 days. The R2 values obtained show an acceptable level of 0.75 and 0.79 for 1982 and 1983 respectively. Thus, a better estimate was obtained than just using the final sampling to show the relationship between dry matter production and grain yields.

In 1982, the precipitation was 27% above the 71 year mean (Figure 4) with fairly good distribution. However, it is evident that there are some factors reducing yields at the high level of dry matter. Weedy grasses combined with excessive vegetative growth may have increased the water consumption to a level that did not leave enough moisture for adequate grain filling. This is a fairly commom problem in semi-arid regions, normally due to an unbalanced fertization with N (Schlehuber and Tucker 1967; Russell 1967; Arnon 1975).

In 1983, yield and dry matter were related linearly. This is an indication that grain yield was not limited by insufficient water.

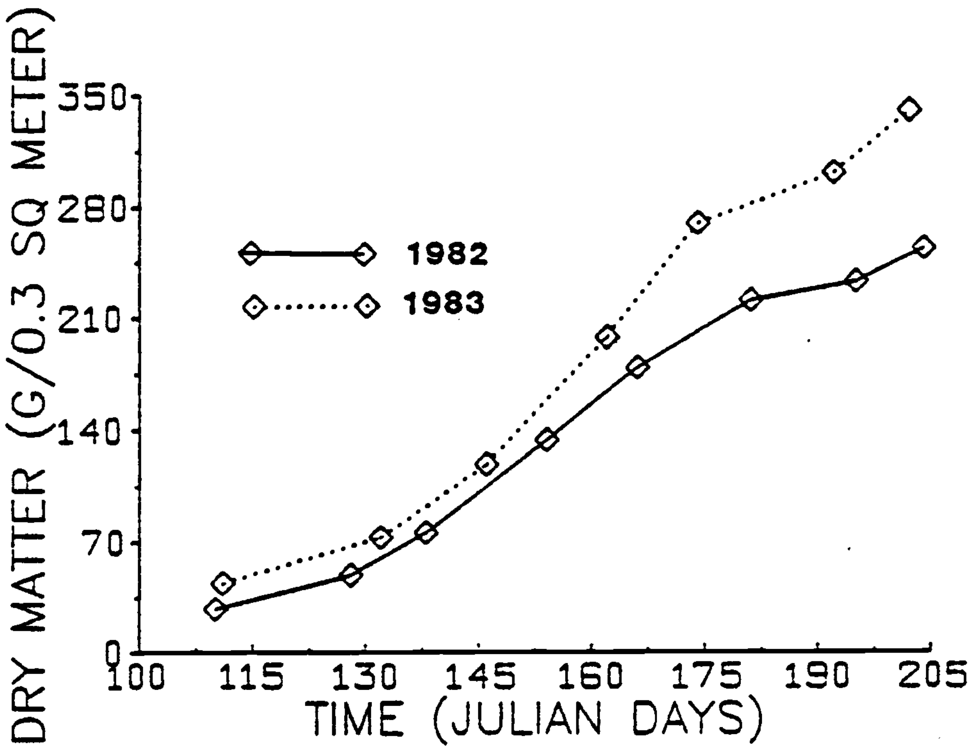


Figure 10: Average total dry matter production, in the NPD field experiment, 1982 and 1983 seasons. Each point is the mean of 32 observations (2 treatments, 4 subtreatments and 4 replications).

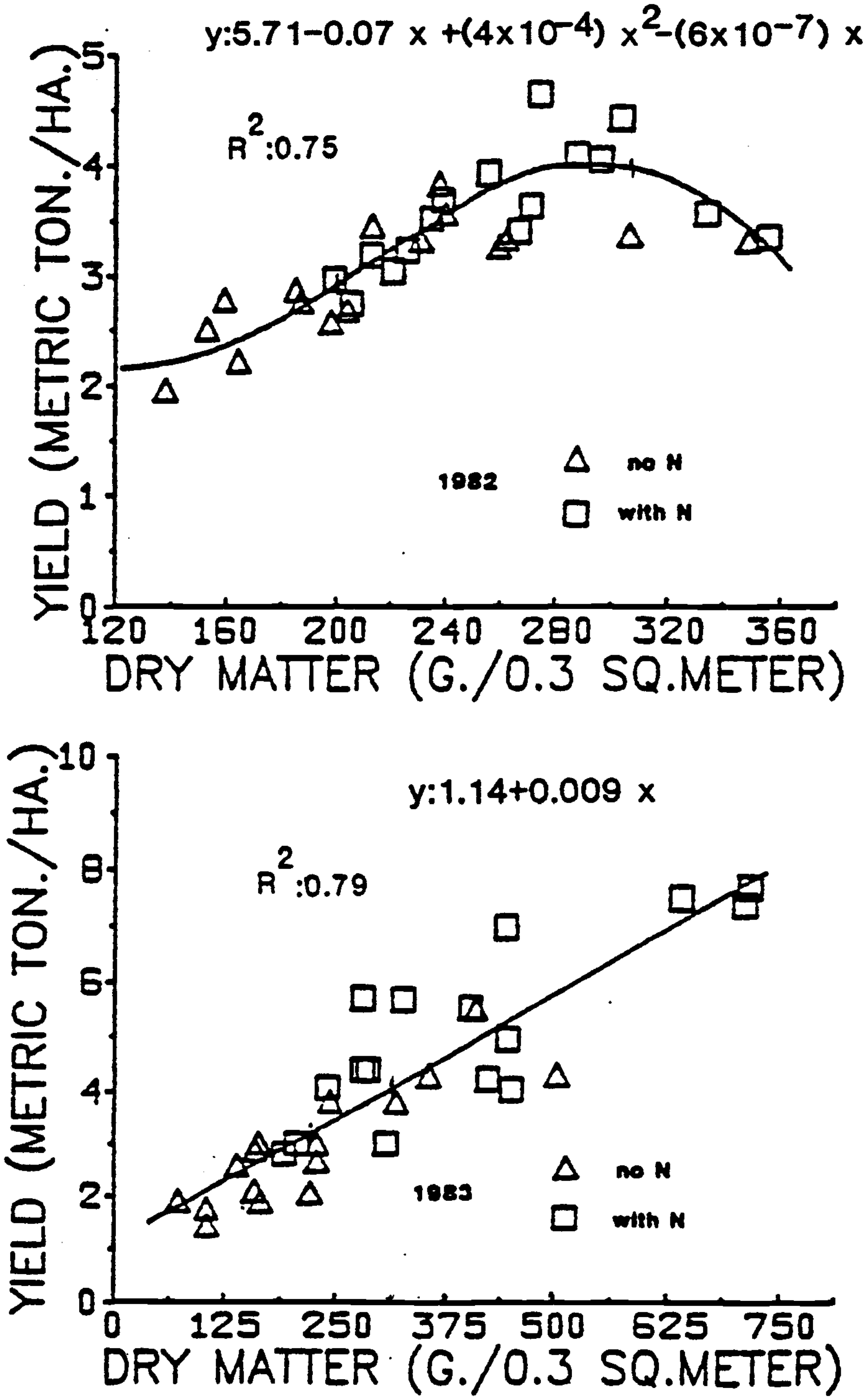


Figure 11: Relationship between total dry matter, calculated as the mean of the last 3 sampling periods and grain yield, in the NPD field experiment, 1982 and 1983 seasons.

These relationships (yield and dry matter) are useful to characterize each year and to understand the results.

If in 1982 there had not been a problem of weedy grasses it is likely the relationship would have been more linear. Thus, both crop years would have responded in a similar fashion to nitrogen. This was the situation in the N experiments where no yield reduction was obtained even at 100 kg N/ha in both years (Figure 12).

7. Dry Matter Partitioning

Figures 13 and 14 describe the dry matter partitioning for the contrast of no N vs. N treatments during 1982 and 1983.

Leaf weight was, in general, higher (P=0.01) during both years in those subtreatments with N. This indicates a greater photosynthetic area and also a greater leaf area for transpiration and a higher water demand. Stem weight was always higher in 1983 in those subtreatments with N but in 1982 the difference between the nitrogen subtreatments was not always clear statistically.

The spike weight was greater for N subtreatments in 1983. In 1982 the N subtreatments had a greater spike weight at the first four dates of sampling but not at harvest time.

The stem weight generally showed a peak about mid-June (166 J.D.) in 1982 and 8 days later in 1983. Beyond that point the stem weight decreased due to the carbohydrate translocation toward the spike. That process was higher in these treatments with N. However, not all the stem weight reduction means sugar translocation to the spike because several reports indicate that under normal

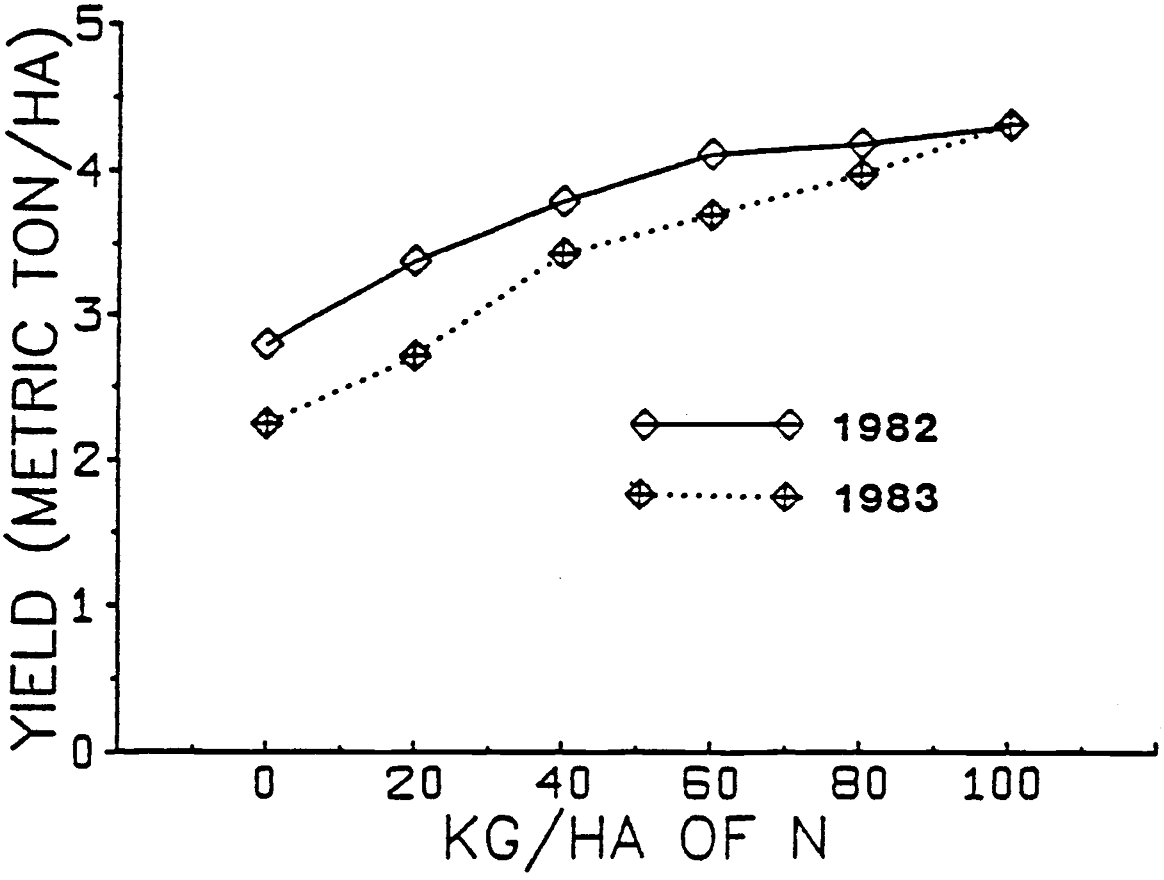


Figure 12: Grain yield of soft white winter wheat (cv. Stephens) in the N experiment during 1982 and 1983 seasons.

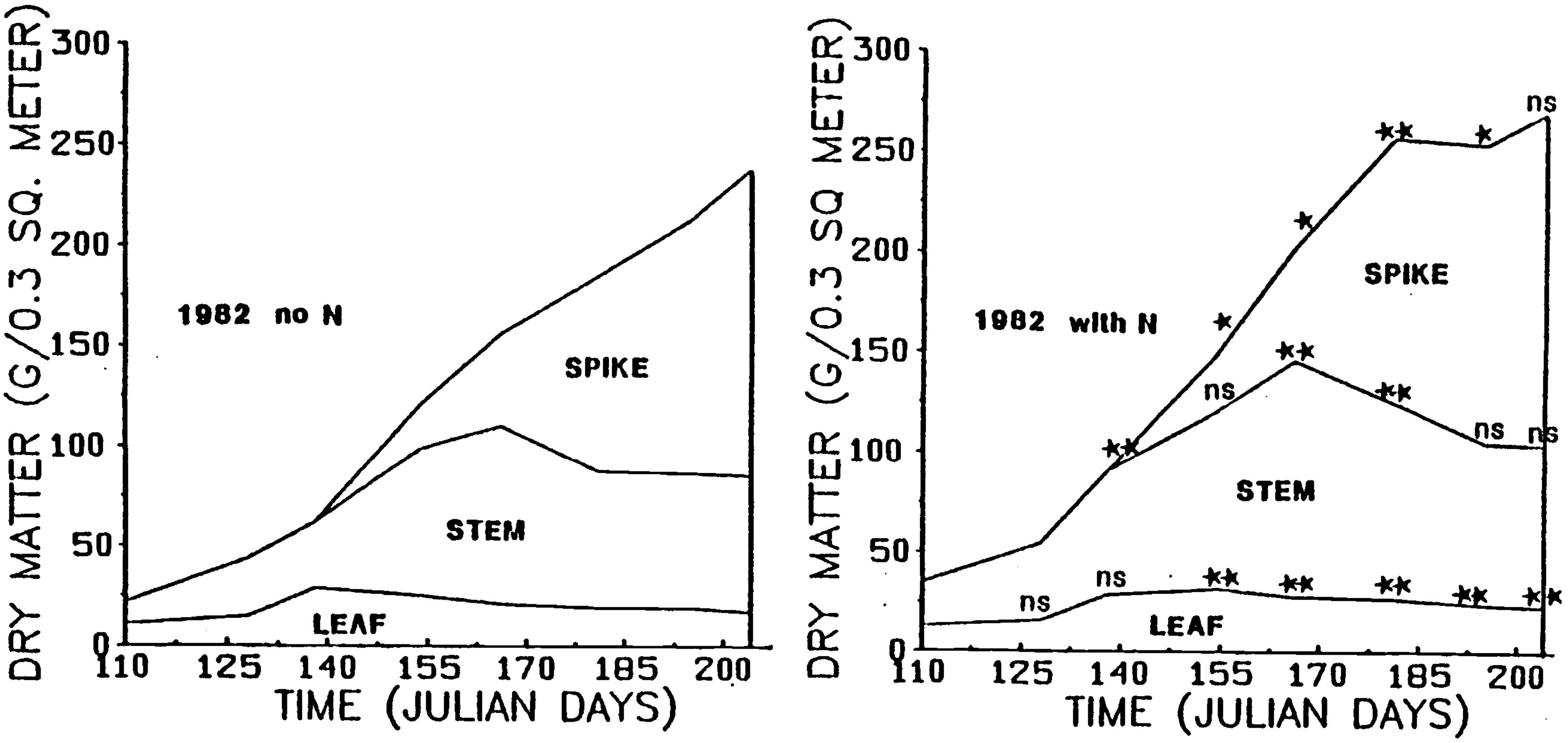


Figure 13: Dry matter partitioning for no N and with N subtreatments during 1982.
(*, ** mean significantly higher at 5 and 1 % level respectively, in with N than no N subtreatments).
(ns No significant difference between no N and with N subtreaments.)

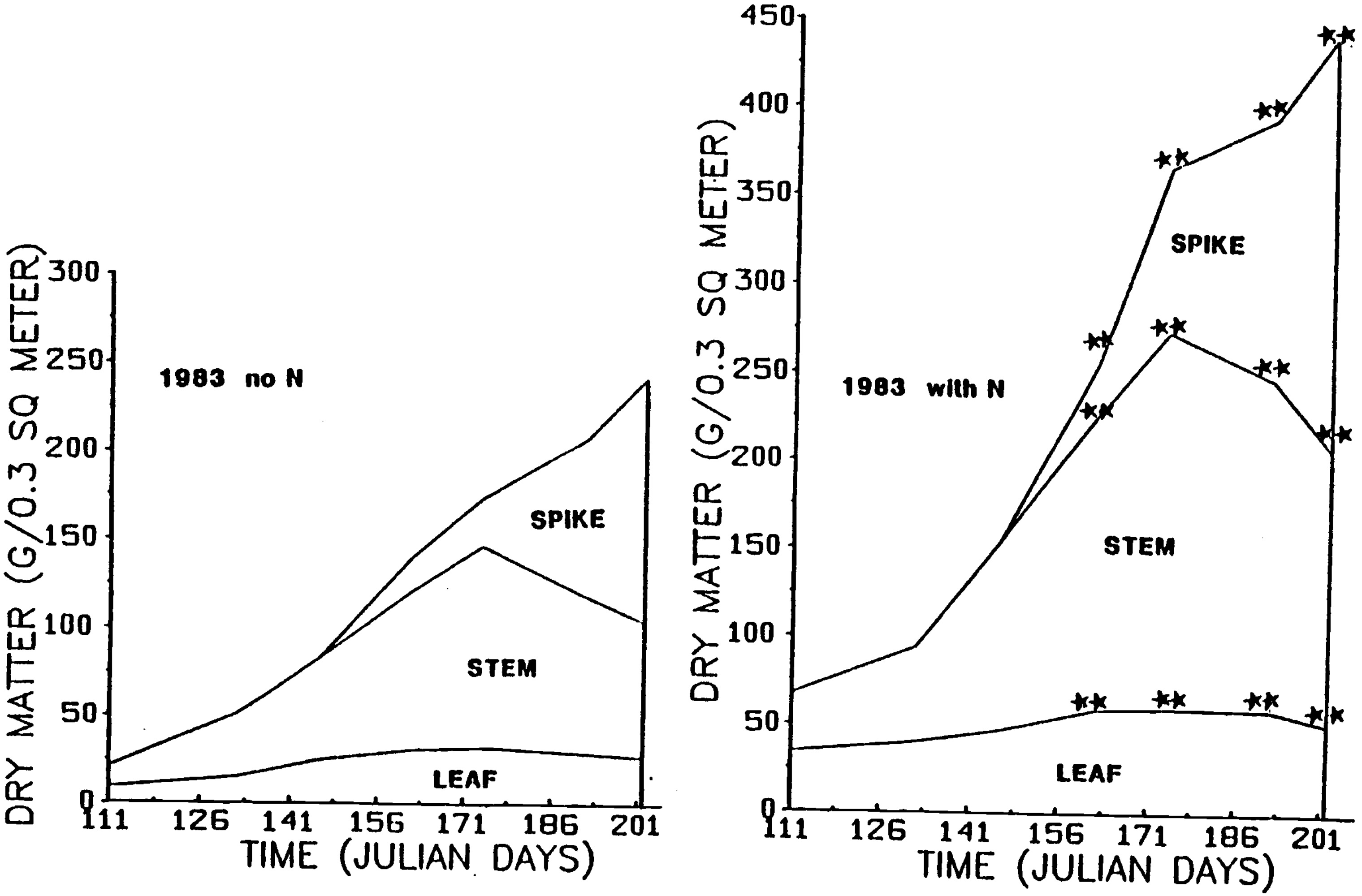


Figure 14: Dry matter partitioning for no N and with N subtreatments during 1983.
(** mean significantly higher at 1 % level in with N than no N subtreatments).

conditions less than 10% of such stem weight reduction is translocated (Evans et al 1975).

In the 1983 season there was a large difference between the no N and with N subtreatments in overall dry matter production. This greater difference in 1983 vs. 1982 is probably due to the optimun weather for N response and perhaps a higher level of leaching of nitrates in the no N subtreatments. That is suggested by the range of dry matter that in 1982 goes from 140 to 160 and in 1983 from 70 to 750 (grams per 0.3 m2)(Figure 11).

8. Yield Components and CWSI

In Figure 5, after June 30 (181 JD), the CWSI sharply increased with no differences between no N vs. N treatments. However, as shown in Figure 15, the evolution of the spike growth (1982) in the treatments with N coincidently decreased in rate of growth after the same date. This sudden decrease in rate of growth may be due to the steep increase in CWSI after June 30. Even though no N vs. with N treatments have the same level of CWSI at that time, the effect on yield reduction possibly was greater in those treatments with N, due to their higher vegetative development (Schlehuber and Tucker 1967; Arnon 1975).

The yield component affected at that stage of growth (grain filling) was kernel weight (Slavick 1966). In fact, there is a 10% reduction in the 1000 kernel weight in 1982 due to N fertilization, whereas in 1983 that reduction is only 6% (Table 9). Rohde (1963) and Aktan (1976) have also reported kernel weight reduction due to N fertilization.

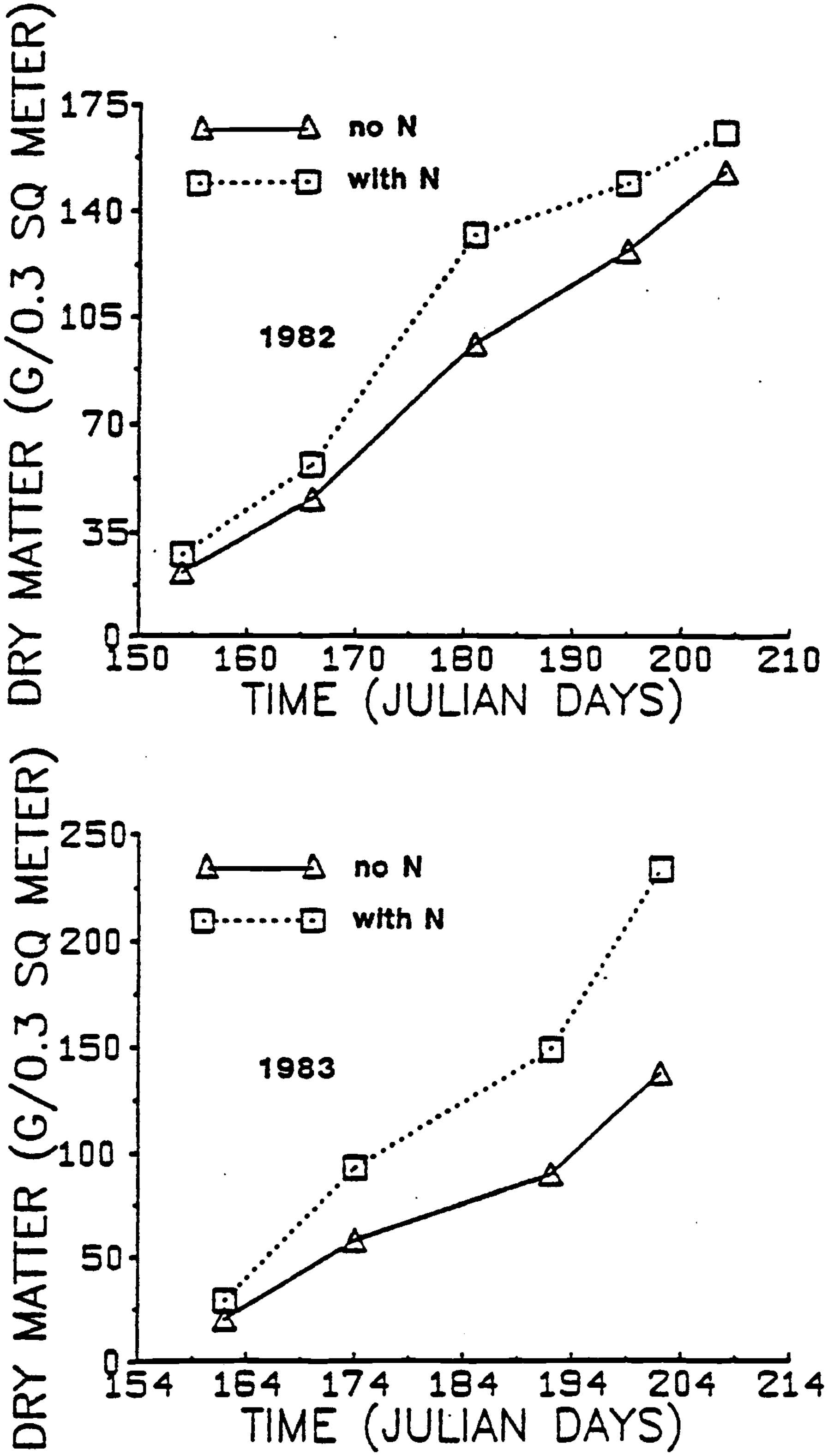


Figure 15: Spike weight development in the NPD field experiment during Post-H through the harvest period during 1982-1983 seasons.

During 1983 (Figure 15) the spike weight for treatments with N had a very steep slope. In this year the mild-cool temperature during June and July (Table 1) and optimum soil water availability permitted enhanced grain filling. This is very evident in these treatments with N which had at this time an even bigger sink than in 1982. However in 1983 that sink was fully replenished.

In summary, looking at Table 9, N increased the yield in 1982 and 1983 17% and 42% respectively. These increments can be explained by the increased number of spikes for the two years of 23% and 38% respectively. In 1983 there is also a 8% increase in the number of grains per spike over 1982. Finally, as was already discussed earlier, there was less reduction in the 1000 kernel weight in 1983 than in 1982, 6% and 10% respectively.

9. Yield Components and Date of Planting

Delay of planting from Date 1 (mid-Sepember) to Date 2 (mid-November) reduced yields 21% and 35% in 1982 and 1983 respectively.

During both years, Date 2 had a poor stand. This stand reduction resulted in fewer tillers and fewer spike numbers (P=0.01).

Results in Table 10 show that the spike number was 37% and 57% higher in Date 1 than in Date 2, conversely the number of grains per spike was 32.5% and 33.3% higher in Date 2 than Date 1 in 1982 and 1983 respectively. The 1000 kernel weight remained unaffected by date of planting during both years.

Table 9: Yield and yield components in the NPD field experiment with and without nitrogen.

1982

Nitrogen (kg/ha)	Yield (T/ha)	Spike number (per 0.3m2)	Grain number (per spike)	1000 grain weight (g)
0	2.99	89.31	24.01	51.05
80	3.59	115.63	23.55	46.11
F	25.79**	33.61**	0.09 ns	90.84**
se (mean)	0.08	3.21	1.10	0.37

1983

Nitrogen (kg/ha)	Yield (T/ha)	Spike number (per 0.3m2)	Grain number (per spike)	1000 grain weight (g)
0	2.94	94.25	17.74	59.16
80	5.09	153.31	19.27	55.67
F	44.76**	51.86**	4.58*	8.63**
se (mean)	0.23	5.80	0.51	0.84

** Significantly different at 1% level
* Significantly different at 5% level
ns Not significantly different

Table 10: Yield and yield components in the NPD field experiment contrasting Date 1 and Date 2 of planting (1982-1983 season).

1982

	Yield (T/ha)	Spike number (per 0.3 m2)	Grain number (per spike)	1000 grain weight (g)
Date 1	3.69	125.69	19.2	47.00
Date 2	2.90	79.25	28.4	50.16
F	29.00**	31.81**	29.65**	7.81 ns
se (mean)	0.10	5.82	1.20	0.80

1983

Date 1	4.86	173.13	15.0	57.65
Date 2	3.17	74.43	22.1	57.18
F	26.97**	22.84*	41.53**	0.22 ns
se (mean)	0.23	14.60	0.78	0.71

** Significantly different at 1% level
* Significantly different at 5% level
ns Not significantly different

In conclusion, although the spike was bigger in Date 2 with higher number of grains per spike, the difference was not enough to overcome the spike number reduction. However it must be considered that the precipitation and yield level of the 2 years were unusually higher than normal.

10. CWSI and Grain Yield Relationships

To develop a model that defines the crop water level and grain yield was one of the main objectives of this study. The importance of understanding this relationship is the fact that in the dryland cereal areas of eastern Oregon, soil water availability during the last few months of the cereal growth cycle is a primary factor in determining the final yield level (Rickman et al 1978).

Developing such a model has two major components; "to aid in understanding a system" (discovering gaps in our knowledge) and; if the model is sufficiently reliable and accurate, "to predict the effect of changes in the system" (Glenn 1981a).

A model must include key independent variables that determine the final result in the dependent variable. CWSI could be a variable that should predict yield if the soil water availability becomes limiting or transpiration demand leads to crop-water stress.

The two seasons considered in this study were somewhat atypical and probably not suitable for this kind of task; although it was

Table 11. Amount of grain protein produced (kg/ha) in the NPD and N field experiments (1982 and 1983 seasons).

NPD field experiments

Nitrogen (kg/ha)	1982	1983
0	213.6	165.8
80	299.4	347.2
F	74.00**	42.47**
se (mean)	7.06	19.68
Protein increase due to N (%)	28.7	52.3

N field experiments

Rate of Nitrogen kg/ha	1982	1983
0	159.6	99.6
20	196.8	125.0
40	229.2	159.7
60	253.9	202.9
80	267.6	228.9
100	302.6	286.0
20 + 20	232.9	165.6
40 + 40	265.2	192.3
F	6.65**	22.31**
se (mean)	17.35	12.49
LSD 0.05	51.02	36.74
Protein increase between 0 and 80 kg N/ha.	40.4	56.5

** Significantly different at 1% level

observed that the CWSI in 1982 and 1983 was rather low with the exception of the control in the N experiment. This should not however, be an obstacle in predicting yield since in the presence of a low CWSI level, the model should predict high yields. However, the CWSI works more accurately with rather dry and hot weather. Under cool and humid conditions, the range between non-water-stressed-baseline and maximum stress (Figure 1) is so narrow that the variability in the data introduced by the scattered random variation, overshadow and confuse the real crop-water stress phenomenon (Idso 1981b). Moreover, if there is another limiting factor other than the soil water, such as nutrient deficiency it may lead to some unexpected results.

For example, in 1983, there are results that suggest a N deficiency. The level of grain protein was low in both experiments, especially in the N experiment (Appendix Table 1 and 2). At first we may think that this is because in 1983 the yield was higher in in the NPD experiment. However, in the N experiment, both the yield and grain protein content were in general lower in 1983 than in 1982. Thus, to explain these results we should think in terms of protein per unit area (Table 11). The lower protein production level can be observed in the N experiment in 1983 and suggests differences in N availability between seasons.

Thus if N is a limiting factor rather than the soil water availability, the contradictory response in the N experinent can be explained. In 1982, considering control and treatments with 40 and

80 kg N/ha, it was observed an average of 22.9 units of total season CWSI with a yield of 3.6 T/ha. Conversely, in 1983 the CWSI average level was 9.7 units of CWSI with a yield of 3.2 T/ha. In spite of the low CWSI level, reflecting optimum weather conditions, the yield in 1983 was lower than in 1982. This is also shown in Figure 12 where only at 100 kg N/ha were yields equal for both years.

In the NPD experiment, another key factor that may determine the yield potential long before the period of the CWSI study begins (March-April) are differences in plant establishment. Date 2 presented systematically a lower total CWSI than Date 1.

Using the NPD experiment data a logarathmic relationship was developed between grain yield and CWSI, averaged on a daily basis (Figure 16):

$$y = 0.13 - 1.77 \ln(x)$$

where y is grain yield in T/ha and x is CWSI. In general the data from 1983 shows a lower range of variation in CWSI and a greater variation in grain yield than in 1982. This is due to the reasons prevoiusly discussed (very low crop-water stress, differences in plant establishment between Date 1 and Date 2 and N deficiencies in some treatments).

Without consideration of the two pairs (circled) which correspond to treatments 1 and 2 in Date 2 (1983), adversely affected by poor plant establishment, the R2 obtained is 0.67. The assumption that CWSI alone could predict grain yield was originally based on limited soil water conditions. If this condition is not present, the other variables that may limit yield potential must be considered.

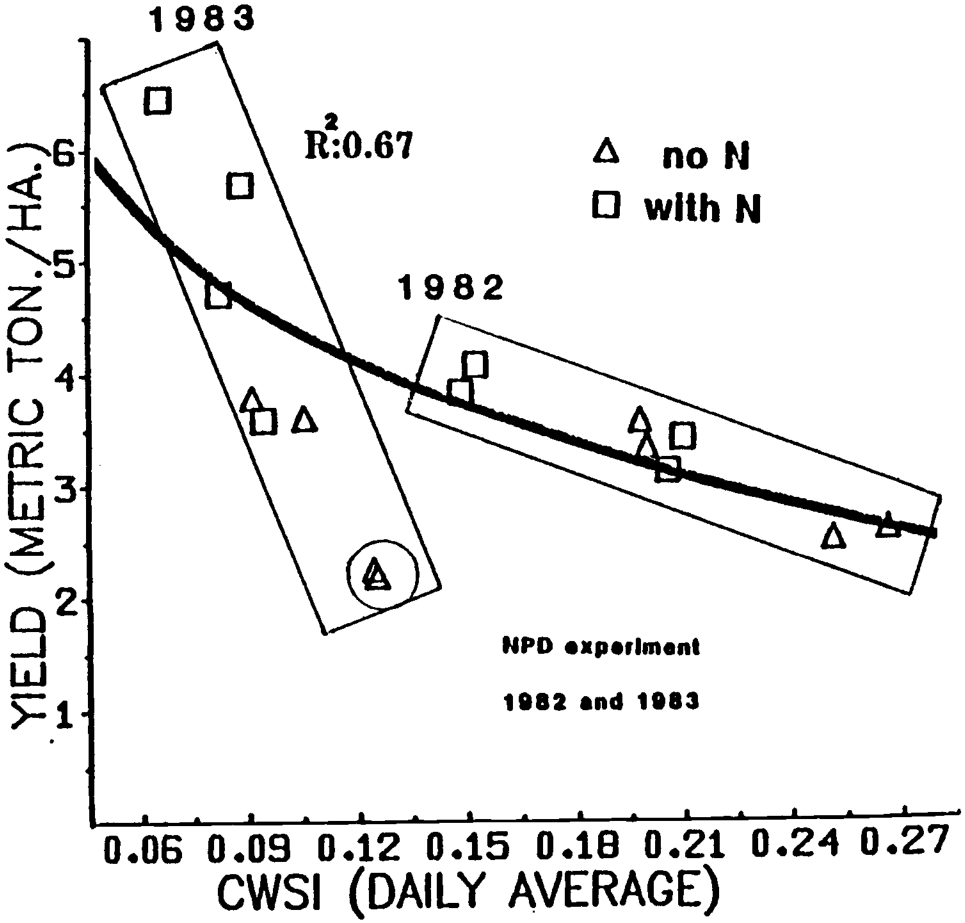


Figure 16: Relationship between grain yield and CWSI averaged on a daily basis in the NPD experiment, 1982 and 1983 seasons.

SUMMARY AND CONCLUSIONS

The objectives of this study were to ; (1) determine the effect of nitrogen and phosphorus fertilization on crop-water stress in relation to crop-water uptake from the soil; (2) describe the crop water stress process in order to attempt to understand, when, and why water stress occurs; (3) analyse the dry matter production, partitioning and yield components in relation to fertilization and crop-water stress; (4) and using the above data to develop an equation to be able to predict the grain yield of soft white winter wheat in the dryland region of Eastern Oregon under a given set of climatic conditions.

Since the study was conducted entirely under field conditions. it was essential that average or nearly normal climatic conditions prevail during the cropping seasons so that different levels of crop water stress could be measured. However, as is often the situation under dryland, rainfed conditions, "normal" climatic conditions only occur as statistical averages. During the two-year period (1981-1983) of this study, precipitation and relative humidity were substantially higher than normal and the maximum temperature during the spring and summer growth period was lower than the long-term average. The combination of these climatic factors produced a much lower level of crop-water stress than is expected.

In spite of the excellent moisture and temperature conditions for crop growth, there were two short periods of time in the 1982 season when the crop showed water stress and the CWSI was able to measure the events.

Several of the other factors being measured showed significant and consistent differences. Nitrogen fertilization increased the total crop-water uptake (P=0.01) during both years in 3 of 4 experiments. The only exception was the N field experiment in 1982, which may have been due to residual fertility from the previous crop. In general, nitrogen increased crop-water uptake from the 0-90 cm soil profile during the Pre-heading periods and from the 90-180 cm depth during the post-heading period, The CWSI level was consistently reduced in the nitrogen treated plots with the one exception noted above. A significant example of the CWSI as a tool to measure water stress occurred in the NPD field experinent in 1982 during a period of 28 days (May 18-June14). The nitrogen-treated plots showed a significantly lower CWSI as compared to the no-nitrogen treatment in this trial.

Total dry matter production vs. grain yield relationships reflected the prevailing climatic conditions during each season. In 1982 a slight decline in yield at the higher level of nitrogen may have been indicative of a mild water shortage at the end of the growing cycle due to an infestation of weedy grasses in the N-treated plots. However, in the 1983 season a direct linear relationship between these parameters indicates that the soil water supply was not limiting.

Leaf weight was generally significantly higher during both seasons when nitrogen was added indicating greater photosynthetic area and increased transpiration. Stem and spike weight were greater in the nitrogen plots in 1983 but not in the 1982 season. In the latter season spike weight was greater during 4 dates of sampling but showed no difference at harvest. A shortage of water just before the grain filling process reduced the 1000 kernel weight by 10% in the N-treatments.

In 1983, significant differences in dry matter production were recorded in the nitrogen vs. no N treatments. Optimum climatic conditions for nitrogen response and perhaps some leaching of nitrates in the no-nitrogen plots were possibly responsible for these differences.

Nitrogen application increased grain yields during both the 1982 and 1983 seasons by 16.7 and 42.0%, respectively. The yield increase was primarily due to the increased number of spikes of 22.8 and 38.0%, respectively. In 1983 there was also an increase of kernels per spike of 7.9%. However, nitrogen application reduced the 1000 kernel weight during both seasons by 10.0 and 5.9%, respectively.

Late planting dates reduced grain yield by 21.4 and 33.9% in 1982 and 1983, respectively. At the later planting date, kernel number per spike was increased by 33 and 32 over the earlier planting date. However, the later planting had reduced spike numbers of 37 and 57%, respectively.

Even though the logarathmic relationship between grain yield and CWSI averaged on a daily basis was developed, it lacked consistency, indicating that other factors must be considered before the stress index can be considered as an accurate predicter of the final yield.

The use of infrared thermometry and the development of a reliable CWSI appears to be possible and feasible to determine crop water stress at the field level. However, the climatic conditions under which this method can be used needs to be more clearly defined.

BIBLIOGRAPHY

Aktan, S. 1976. Nitrate-nitrogen accumulation and distribution in the soil profile during a fallow grain rotation as influenced by different levels of soil profile moisture. M.S. Thesis. Oregon State University, Corvallis. pp.93.

Arnon, I. 1972. Crop production in dry regions. Volume I: Background and Principles. Leonard Hill (ed.). pp. 650.

Arnon, I. 1975. Physiolgical principles of dryland crop production. In: Physioloigal aspects of dryland farming. V.S. Gupta (ed.). p.2-145.

Aspinall, D; P.B. Nicholls and L.H. May. 1964. The effects of soil moisture stress on the growth of barley. I. Vegetative development and grain yield. Aust. J. Agric. Res. 15:729-745.

Black, A.L. 1970. Adventitious roots, tillers and grain yields of spring wheat as influenced by N-P fertilisation. 62:32-36.

Bonanno, R.A. 1982. Effect of irrigation scheduling, using remotely sensed canopy-air temperature differentials, on water relations, yield, and quality of snap beans (Phaseolus vulgarisL.) Ph.d. Thesis, Oregon State University, Corvallis. pp.166

Brown, P.L. 1972. Water use and soil water depletion by dryland wheat as affected by nitrogen fertilization. Agron. J. 63:43-46.

Cornforth, I.S. 1968. Relationship between soil volume used by roots and nutrient accessibility. J. Soil Sci. 19:291-301.

Duncan, W.G. and A.J. Ohlrogge. 1958. Principles of nutrient uptake from fertilizer bands. II. Root development in the band. Agron. J. 50:605-608.

Ehrler, W.L. 1973. Cotton leaf temperature as related to soil water depletion and metereological factors. Agron. J. 65:404-409.

Ehrler, W.L.; Idso, S.B.; Jackson, R.D. and Reginato, R.J. 1978b. Diurnal changes in plant water potential and canopy temperature of wheat as affected by drought. Agron. J. 70:999-1004.

Evans, L.T.; Wardlaw,I.F. and Fischer, R.A. 1975. Wheat. In L.T. Evans: Crop Physiology, Cambridge University Press, Cambridge. p.101-149.

Fischer, R.A. 1973. The effect of water stress at various stages of development on yield processes in wheat. In: Plant reponse to climatic factors. R.O. Slayer (ed.), UNESCO, Paris. p.233-241.

Glenn, D.M. 1981a. The effect of precipitation variation on soil moisture, soil nitrogen, nitrogen response, and winter wheat yields in eastern Oregon. Ph. D. Thesis, Oregon State University, Corvallis. pp.140.

Glenn, D.M. 1981b. The effect of nitrogen and phosphorus fertilization on crop development of early and late planted winter wheat. Oregon Agr. Exp. Sta. Special Report 661 .p.12-16.

Gardner, W.R. 1960a. Soil water relations in arid and semiarid conditions. UNESCO Arid Zone Res. 15:37-61.

Gardner, E.H.; T.W. Thompson; H. Kerr; J. Hesketh; F.H. Hagelstein; F. Zimmerman and G. Cook. 1975. The nitrogen and sulfur fertilization of dryland wheat in Oregon's Columbia Plateau. Proc. Twenty-sixth Annual Northwest Fertilizer Conference, Salt Lake City, Utah.

Gardner, E.H.; N.R. Goetze and P.E. Rasmussen. 1980. Oregon State University. Guide for winter wheat (non-irrigated-Columbia Plateau). FG 54.

Gates, D.M. 1969. Transpiration and leaf temperature. Ann. Rev. Plant Physiol. 19:211-238.

Hackett, C. 1969a. Qualitative aspects of the growth of cereal root systems. In: Root Growth. Whittington, W.J. (ed.), Butterworths, London. p.134-147.

Hatfield, J.L.; R.J. Reginato; R.D. Jackson; S.B. Idso and P.J. Pinter. 1978. Remote sensing of surface temperature for soil moisture, evapotranspiration and yield estimation. 5th Canadian Symposium on Remote Sensing, Victoria. p.460-464.

Hsiao, T.C. 1973. Plant response to water stress. Ann. Rev. Plant Physiol. 24:519-570.

Hunter, A.S.; L.A. Alban; C.J. Gerard; W.E. Hall; H.E. Cushman and R.G. Petersen. 1961. Fertilizer needs of wheat in the Columbia Basin dryland area of Oregon. Oregon Exp. Sta. Tech Bulletin. 57:3-47

Hurd, E.A. 1968. Growth of roots of seven varieties of spring wheat at high and low moisture levels. Agron. J. 60:201-205.

Hurd, E.A. and E.D. Spratt. 1975. Root patterns in crops. In: Physiological aspects of dryland farming. U.S. Gupta. p.166-235.

Jackson, R.D.; R.J. Reginato and S.B. Idso. 1977. Wheat canopy temperature: A practical tool for evaluating water requirements. Water Resour. Res. 13:651-656.

Jackson, R.D. 1982. Canopy temperature and water stress. In: Advances in Irrigation. Daniel Hillel (ed.). Academic Press, Inc. p.43-85.

Idso, S.B. 1982. Non-water-stressed baselines: A key to measuring and interpreting plant water stress. Agric. Metereol. 27:59-70.

Idso, S.B. and D.G. Baker. 1967. Relative importance of irradiation, convection and transpiration in heat transfer from plants. Plant Physiol. 42:631-640.

Idso, S.B.; R.D. Jackson; P.J. Pinter, Jr.; R.J. Reginato and J.L. Hatfield. 1981a. Normalising the stress-degree-day for environmental variability. Agric. Metereol. 24:45-55.

Idso, S.B.; R.D. Jackson and R.J. Reginato. 1977. Remote sensing of crop yields. Science 196:19-25.

Idso, S.B.; P.J. Pinter, Jr.; J.L. Hatfield; R.D. Jackson and R.J. Reginato. 1979. A remote sensing model for prediction of wheat yields prior to harvest. J. Theor. Biol. 77:217-228.

Idso, S.B.; R.J. Reginato; R.D. Jackson and P.J. Pinter, Jr. 1981c. Measuring yield-reducing plant water potential depressions in wheat by infrared thermometry. Irrig. Sci. 2:205-212.

Idso, S.B.; R.J. Reginato; D.C. Reicosky and J.L. Hatfield. 1981b. Determining soil-induced plant water potential depression in alfalfa by means of infrared thermometry. Agron. J. 73:826830.

Kmoch, H.G.; R.E. Ramig and F.F. Koehler. 1957. Root development of winter wheat as influenced by soil moisture and nitrogen fertilizion. Agron. J. 49:20-25.

Koehler, F.E. 1960. Nitrogen uptake and moisture use by wheat. Proc. 11th Annual Pacific Northwest Fertilizer Conf., Salt Lake City, Utah. :141-146.

Kramer, P.J. 1963. Water stress and plant growth. Agron. J. 55:31-35

Kramer, P.J. 1969. Plant and soil water relationships. A modern synthesis. McGraw-Hill. pp.482.

Kramer, P.J. and T.S. Coile. 1940. An estimation of the volume of water made available by root extension. Plant Physiol. 15:743-747.

Legg, J.O. and J.J. Meisinger. 1982. Soil Nitrogen Budgets. In: F.J. Stevenson (ed.). Agonomy 22:503-566

Leggett, G.E.; H.M. Reisenauer and W.L. Nelson. 1959. Fertilization of dryland wheat in eastern Washington. Washington Agr. Exp. Sta. Bulletin 602. p22.

Miller, M.H. 1971. The effect of nitrogen on phoshorus absorption by plants. In: The plant Root and its Environment. University Press of Virginia. p.246-270.

National Oceanic and Atmospheric Administration (NOAA). 1982. Monthly normals of temperature, precipitation, and heating and cooling degree days 1951-80, Oregon. Climatography of the United States No 81 (By State). pp.25.

Nielsen, K.F. 1971. Roots and root temperatures. In: Carson, E.W. The Plant Root and its Environment. University Press of Virginia. p.293-333.

Olson, R.A. and L.T. Kurtz. 1982. Crop Nitrogen Requirements, Utilization and Fertilization. In: Nitrogen in Agricultural Soils. F.J. Stevenson (ed.). Agronomy 22:657-604.

Pearson, R.W. 1971. Significance of rooting pattern to crop production and some problens of root research. In: Carson, E.W. The Plant Root and its Environment. University Press of Virginia. p.247-270.

Petersen, R.G. 1977. Use and misuse of multiple comparison procedures. Agron. J. 69:205-208.

Pinthus, M.J. 1969. Tillering and coronal root formation in some common and durum wheat varieties. Crop Sci. 9:267-272.

Piper, C.S. and M.P.C. Vries, De. 1964. The residual value of superphoshate on a red-brown earth in south Australia. Aust. J. Agric. Res. 15:234-272.

Power, J.F.; D.L. Grunes and G.A. Reichman. 1961. The influence of phosphorous fertilization and moisture on growth and nutrient absoption by spring wheat: I. Plant growth, N uptake, and moisture use. Soil Sci. Soc. Amer. Proc. 25:207-210.

Pumphrey, F.V. and P.E. Rasmussen. 1982. Winter wheat fertilization in the Northeast Intermountain Region of Oregon. Circular of Information 691. Agr. Exp.Sta., Oregon State University. p.13.

Ramig, R.E. and H.F. Rhoades. 1963. Interrelationships of soil moisture level at planting time and nitrogen fertilization on winter wheat production. Agron. J. 55:123-127.

Rennie, D.A. and R.J. Soper. 1958. The effect of nitrogen addition on fertilizer--phosphorus availability. II. J. Soil Sci. 9:155-167.

Rickman, R.W.; R.R. Allmaras and R.E. Ramig. 1978. Root-sink description of water supply to dryland wheat. Agron. J. 70:723-728.

Robinson, L.H. 1961. The geography, morphology and environmental relationships of the Walla Walla soil series in Oregon. M.S. thesis, Oregon State University. pp.124.

Rohde, C.R. 1963. Effect of nitrogen fertilization of yield, components of yield, amd other agronomic characteristics of winter wheat. Agron. J. 55:455-458.

Russel, J.S. 1967. Nitrogen fertilizer and wheat in a semiarid environment. Aust. J. Exp. Agric. and Anim. Husb. 7:453-462.

Russelle, M.P. and F.E. Bolton. 1980. Soil temperature effects on winter wheat and winter barley emergence in the field. Agron. J. 72:823-827.

Schlehuber, A.M. and B.B Tucker. 1967. Culture of wheat. In: K.S. Quisenberry and L.P. Reitz (ed.). Wheat and wheat improvement. Agronomy J. 13:117-179.

Slavik, B. 1966. Response of grasses and cereals to water. In: The Growth of Cereals and Grasses. Milthorpe, F.L. and J.D. Irins (editors), Butterworths, London. p.227-240.

Slatyer, R.O. 1967. Plant-water Relationships. Academic Press, New York. pp.366.

Slatyer, R.O. 1969. Physiolgical significance of internal water relations to crop yields. In: Physiological Aspects of Crop Yields. Dinauer, R.C. (ed.), Am. Soc. Agron., Madison, Wis. p.53-88.

Slayter, R.O. 1973. Effects of short periods of water stress on leaf photosynthesis. In: Plant Response to climatic factors. R.O. Slayter (ed.), UNESCO, Paris. p.271-276.

Tanner, C.B. 1963. Plant temperatures. Agron. J. 55:210-211.

Troughton, A. 1957. The underground organs of herbage grasses. Commonwealth Bur. Pastures Field Crops Bull. 44. p.105-120.

Vaadia, Y.; F.C. Raney and R.M. Hagan. 1961. Plant water deficit and physiological processes. Ann. Rev. Plant Physiol. 12:265-292.

Viets, F.G., Jr. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14:223-264.

Walker, B.K. and J.L. Hatfield, Jr. 1979. Test of the stress-degree-day concept using multiple planting dates of red kidney beans. Agron. J. 71:967-971.

Wardlaw, I.F. 1967. The effect of water stress on translocation in relation to photosynthesis and growth. Aust. J. Biol. Sci. 20:25-39.

Weaver, J.E.; J. Kramer and M. Reed. 1924. Development of root and shoot of winter wheat under field environments. Ecology 5:26-50

Wells, S.A. and S. Dubetz. 1966. Reaction of barley varieties to soil water stress. Can. J. Plant Sci. 46:507-512.

Wiersum, L.K. 1961. Utilization of soil by the plant root system. Plant and Soil 15,2:189-192.

APPENDIX

Appendix Table 1. NPD field experimental data for the 1982 and 1983 seasons.

Date of planting	Subtreatments kg/ha N & P205		1982				1983			
			Yield T/ha	1000 KW (g)	Test W (kg/hl)	Protein (%)	Yield T/ha	1000 KW (g)	Test W (kg/hl)	Protein (%)
1.	0	0	3.55	49.58	72.47	6.48	3.59	59.40	73.37	5.33
	0	100	3.32	48.77	72.22	6.14	3.77	58.04	71.27	4.99
	60	0	3.43	45.12	73.83	7.40	5.25	56.85	72.73	5.70
	80	0	4.05	44.72	74.26	7.66	6.43	57.46	75.15	6.70
	60	100	4.03	45.11	74.48	7.94	5.75	57.15	74.82	6.08
	80	100	3.81	44.94	74.29	8.16	5.66	55.70	74.50	6.90
2.	0	0	2.59	52.65	74.03	8.38	2.17	60.09	72.40	6.39
	0	100	2.50	53.22	73.47	8.17	2.23	59.11	72.90	6.23
	60	0	3.20	50.59	74.35	8.50	2.34	56.83	72.73	6.79
	80	0	3.10	46.30	74.03	9.19	3.57	55.23	73.21	6.14
	60	100	3.24	49.56	74.30	8.75	3.33	50.36	71.59	7.34
	80	100	3.40	48.48	74.02	8.59	4.69	55.79	73.21	6.96
	F		1.54 n.s.	0.98 n.s.	1.84 n.s.	5.10**	1.59 n.s.	1.60 n.s.	3.11*	1.28 n.s.
	se (mean)		0.20	0.97	0.42	0.20	0.46	1.66	0.67	0.48
	LSD(0.05)		-	-	-	0.29	-	-	1.93	-

Appendix Table 2. N field experimental data for the 1982 and 1983 seasons.

Treatment	1982				1983			
(kg/ha) plt/till	Yield T/ha	1000 KW (g)	Test W kg/hl	Protein (%)	Yield T/ha	1000 KW (g)	Test W kg/hl	Protein (%)
0 + 0	2.80	48.60	71.54	5.71	2.25	56.15	71.76	4.44
20 + 0	3.39	48.62	72.17	5.80	2.72	52.93	71.92	4.60
40 + 0	3.80	48.02	72.91	5.98	3.44	51.84	72.89	4.64
60 + 0	4.13	46.88	72.45	6.14	3.71	50.30	75.31	5.51
80 + 0	4.20	45.81	72.67	6.39	3.99	51.62	75.79	5.71
100 + 0	4.33	44.28	74.09	6.99	4.34	48.97	76.27	6.59
20 + 20	3.79	45.50	72.38	6.16	3.55	50.51	73.21	4.70
40 + 40	3.92	47.10	74.28	6.75	3.92	53.16	74.82	4.91
F	5.52**	5.63**	5.76**	7.17**	10.91**	6.75**	3.09*	16.64**
SE	0.21	0.66	0.39	0.17	0.21	0.85	1.01	0.18
LSD 0.05	0.62	1.94	1.15	0.49	0.62	2.49	2.96	0.53

1. plt = planting, til = tillering

Appendix Table 3: Source of variation and degrees of freedom for 2 types of analysis of variance in the NPD experiment.

Source of Variation	df 4 subtreatments
Rep	3
Date	1
P	1
N	1
P X N	1
Rep X Date	3
Rep X P	
Rep X Date X P	
Rep X N	
Rep X Date X N	
Rep X N X P	
Rep X Date X P X N	18
Date X P	1
Date X N	1
Date X N X P	1
Total	31

Source of Variation	df 4 subtreatments	df 6 subtreaments
Rep	3	3
Date	1	1
Rep X Date	3	3
Treatment	3	5
Rep X Treatment		
Rep X Date X Treatment	18	26
Date X Treatment	3	5
Total	31	43

Appendix table 4: Source of variation and degrees of freedom of analysis of variance in the N experiment.

Source of Variation	df 3 treatments	df 8 treatments
Rep	3	3
Treatment	2	7
Rep X Treatment	6	21
Total	11	31

Appendix table 5: Date of planting X N interaction in the NPD field experiments 1982-1983 for grain protein content. 80 kg of nitrogen /ha was applied to the with N subtreaments.

	1982		1983	
	no N	with N	No N	with N
Date 1	6.31	7.91	5.16	6.80
Date 2	8.27	8.88	6.31	6.55
F	19.45**		7.70*	
se (mean)	0.11		0.25	
LSD 0.05	0.33		0.75	