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Monitoring high water table effects on corn growth and water quality in growth chambers and field lysimeters

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Monitoring high water table effects on corn growth and water quality in growth chambers and field lysimeters

by

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GENERAL INTRODUCTION

Understanding the effects of high water table conditions on crops is of a prime importance not only to determine the removal rate of excess water for designing drainage systems in developed countries but also in terms of developing measures by which to increase crop yield in poorly drained soils or waterlogged areas in developing countries, where drainage systems cannot be purchased due to lack of funds. To achieve either of these goals, an understanding of crop response as a function of water table depth and duration is vital.

Excessive rainfall usually results in high water tables or even in temporary flooding of poorly drained soils. Duration of flooding varies depending upon the intensity and duration of rainfall and on the ability of soil to drain excessive water.

Many studies have been conducted to determine the response of crops to surface flooding (Williamson and Kriz, 1970; Hiler and Clark, 1971; Cannell et al., 1980; Joshi and Dastane, 1966; Evans and Skaggs, 1984; Mukhtar et al., 1990). Researchers have found increased growth and yield reductions in many crops undergoing increased durations of surface flooding. Therefore, drainage of excessive water, especially during surface flooding, is essential to improving crop yield. Kanwar et al. (1984) found in a study conducted in Iowa that inadequate drainage systems were responsible for average crop yield reductions equal to about one-third of the maximum yield potential of poorly drained soils.

At the same time, excessive natural or artificial water drainage is undesirable because it reduces soil water available to growing plants and leaches fertilizers, carrying them away from the root zone to receiving streams and/or to deeper ground water systems, where they act as pollutants. Many researchers have found that drainage systems are major carriers of fertilizers and of other agricultural chemicals (pesticides) away from the root zone (Kanwar et al., 1985; Protasiewicz et al., 1988; Gilliam et al., 1979). Leaching of agricultural chemicals (fertilizer and pesticides) not only is a loss to farmers, but also has the potential to contaminate potable water. According to Kanwar et al. (1990), the amount of herbicides used in Iowa for corn and soybean production has the potential to contaminate surface and groundwater supplies.

It is necessary, therefore, to develop agricultural management practices that are profitable, that maintain agricultural productivity, and that do not degrade potable water supplies. It is hypothesized that good water table management, associated with control of both depth and duration of water table, will result in increased yields and improved profitability while reducing adverse environmental effects.

Some studies have been conducted on controlled drainage plots in which the water table was drained after rising to a required depth (Gilliam et al., 1979; Merva and Belcher, 1990). These studies concluded that controlled drainage reduced nitrate concentration in drained effluent.

Much research has been devoted to determining the effectiveness of drainage systems, the methods of water removal, and the optimal conditions of plant growth. The upper limit of plant tolerance to high soil moisture has received limited attention although such studies have the potential to evaluate measures designed to control agricultural fertilizer and chemical losses through drainage systems. Thus, the relation between high water table (depth and duration) and water quality should be studied, as should the response of crop growth and yield.

Few studies regarding crop response to high water table have been conducted to determine either crop susceptibility at different growth stages to surface flooding or crop response to maintaining water table depth at a particular depth throughout the growing season. Mukhtar et al. (1990) concluded that flooded corn was more susceptible to grain yield reduction at the early vegetative stage than at other stages; however, Evans and Skaggs (1984) concluded that it was more susceptible at the late vegetative stage.

Other studies have been conducted to characterize the relation between excessive soil moisture and crop yield. Sieben (1964) introduced the concept of the sum of exceedance values in water level, currently known as the "sum of excess water" (SEW_{30}), which relates yield reduction to high water. Hiler and Clark (1971) proposed methods to characterize crop susceptibility (CS) values in controlled situations and in the field. Ravelo et al. (1982) developed the relation between relative yield and stress day index (SDI) introduced by Hiler et al. (1974). The

SDI method measures the intensity and duration of crop yield deficit. Additionally, Hardjoamidjojo et al. (1982) developed the relation between relative yield and SDI. No study has been conducted to determine the reliability of the concept.

Limited studies have been conducted to investigate the effect of depth and duration of high water table on the sensitive stage of crop. Nor has much research been undertaken to study the behavior of nutrients in terms of plant uptake, nitrate status in the soil as a function of both depth and duration of water table treatments, and losses through drained water. The present study, therefore, included experiments conducted in climatically controlled chambers and in field type lysimeters. The objectives of the study were:

1. to determine the effect of two water table positions surface flooding and water table at 15 cm below the soil surface on corn growth and yield during vegetative growth with four different flooding durations;
2. to quantify nitrogen uptake and distribution of roots for four different flooding treatments and two different water table positions;
3. to investigate the effects of water table positions (surface flooding and water table at 15 cm below the surface), each with four different durations, on the efficiency of nitrate and plant uptakes;

4. to evaluate the relation between SDI values and relative yield, by using the SEW_{30} concept, a component of the SDI method.

Explanation of Dissertation Format

This dissertation contains the candidate's original work on high water table effects on corn growth and water quality. The entire dissertation contains five separate parts. Each part was written by the author in a format suitable for submission for publication in technical journals. The first, third, and fourth partss have been submitted for publiction in the Transaction of the American Society of Agricultural Engineers. Second part has been submitted for publication in the Journal of Agricultural Water Management, Netherland. Part five has been proposed for presentation at the 5th International Drainage Workshop which will be held from February 8-15, 1992 in Lahore, Pakistan.

Each part contains an abstract, introduction, experimental method, results, discussion, and summary. The references for the introduction, experimental methods, and results of all the five parts and part of the literature review are located at the end of the dissertation.

LITERATURE REVIEW

Crop Response to Excessive Soil Water

Plant growth and grain yields of many crops are significantly reduced when grown in waterlogged soils. Several physiological changes, such as death of roots and reduced uptake of nitrogen, phosphorous, and potassium, can injure plants grown under conditions of excessive moisture. The extent of plant injury caused by excessive soil wetness depends mainly on the type of crop, the stage of plant development, and the duration and depth of flooding.

Maranville et al. (1986) studied the effect of flooding on eight sorghum cultivars. Flooding was initiated 30 days after seeding and terminated when most cultivars were at or near the boot-growth stage. Their investigations found that flooding significantly reduced dry-matter production and delayed bloom date by 5.5 days on average. Grain yield was reduced about 57 percent for all cultivars.

Kramer (1951) studied the effect of flooding of the soil on injury to different plant species. He found that flooding caused more shoot injury to tobacco than to either tomato or sunflower plants. He concluded that plants rapidly producing adventious roots suffer relatively little injury and recover relatively well during post flooding.

Meek et al. (1980) conducted an experiment evaluating the effects of three water table depths of 30, 60, and 90 cm on growth of cotton. Optimal water-table depth was 90 cm. At water-table depths of 30 and 60 cm, seed cotton yield was reduced by 43 and 25 percent, respectively.

The investigators also found that decreasing the water table depth to 90 cm increased the total uptake of all elements studied (N, P, and K).

So and Orchard (1985) investigated the effect of flooding on sunflower and sorghum during nine days of waterlogging under greenhouse conditions. Waterlogging was imposed at different stages of growth, and a single waterlogging treatment was compared with multiple treatments. In this study waterlogging resulted in reduced plant growth and diminished ability of roots to absorb water results which in turn caused reduced water-use and reduced growth.

Williamson (1964) studied the effects of poor aeration on plant growth. He grew different plant species in sheltered and nonsheltered lysimeters where he established and maintained throughout the growing season constant water-tables of 15, 30, 46, 61, and 76 cm below the soil surface 10 to 21 days after planting. Yields of grain sorghum, soybean, cabbage, sweet corn, and dwarf field-corn for 15-cm water-table depths were reduced by 25, 35, 40, 65, and 75 percent, respectively. These reductions indicate that grain sorghum was much more adaptable to poor soil aeration due to high water-table than was corn.

In India, Joshi and Dastane (1966), Chaudhary et al. (1975), and Bhan (1977) studied the response of corn to controlled flooding. Joshi and Dastane (1966) flooded corn in sandy loam soil for one, four, and eight consecutive days in the early growth stage before flowering and then in the early dough stage one day at a time, on the 37^{th}, 47^{th}, 65^{th}, and 76^{th} days after planting. These investigators all observed that damage to plants and grain yields was greatest when soil was flooded for eight days. They also observed that intermittent flooding was less harmful than continuous flooding for the same duration.

Using metal barrel lysimeters filled with silt loam topsoil with fine gravel at the bottom, Chaudhary et al. (1975) conducted a field study. They flooded corn from one to six days at the two and eight week growth stages.

Bhan (1977) studied the effects of different durations of surface flooding at different growth stages of a maize crop. He found a reduction of 10.0 q/ha (36.9%) in maize yield at silk stages when flooded at knee height level for five days compared with an unflooded control.

In Iowa, Ritter and Beer (1969) and Deboer and Ritter (1970) conducted field experiments to study the response of corn to one, two, and three days of flooding at three different growth stages, and during periods of natural flooding, respectively. Both studies reported that the length of flooding is more important at the early than at the late stages of growth and that water standing in naturally flooded fields is more harmful to corn plants than the water applied artificially.

Bowen et al. (1971), Howell and Hiler (1974), Sharma and Swarup (1989), and Leyshon and Sheared (1974) have found that longer durations of flooding increased the degree of stress to different plant parameters.

Leyshon and Sheard (1974) flooded barley for two to seven days during different stages of its development. They found that larger growth reduction at the establishment stage (14-days) than at the early vegetative growth stage (28 and 35 days). They also observed that after the removal of stress, young plants recovered better than did old plants.

Sherma and Swarup (1989) studied the effect of flooding on the growth stages of millet. They found that flooding for one, two, four or six days at tillering or flowering resulted in a 6.3, 15.0, 21.6, or 26.6 percent reduction in grain yield respectively, and significantly reduced tillering, canopy height, dry matter content, ear length, and grain weight.

Luxmoore et al. (1973) found that flooding wheat for 10 to 15 days during grain-fill had no influence on yield but that flooding for 20 to 30 days reduced wheat yield by 15 to 23 percent.

Zolezzi et al. (1978) found that, in comparison with unflooded lysimeters, lysimeters flooded for 7, 12, and 17 days reduced sorghum yields 2.5, 12.9, and 21.9 percent, respectively.

Soomro and Waring (1987) conducted a glass-house study of the effect of temporary flooding on the growth and development of cotton. Plants were flooded twice, 15 and 45 days after planting. The investigators reported that plant dry-weight and cotton plant growth characteristics such as height, number of leaves, leaf area, and fruiting points were greatly reduced because of the flooding treatments.

Bhuiyan and Alagcan (1990) conducted experiments to investigate the response of corn to shallow water-table encountered by farmers growing upland crops adjacent to irrigation canals or rice areas. They reported that lowering water depth slightly produced a strong increasing response in both canopy height and yield; this response manifested the critical role of oxygen supply in plant performance. The investigators indicated that during the vegetative growth state of corn it was highly probable that yields higher than 7.3 t/ha of corn could be achieved for the average water-table depth of 15 cm.

Goins et al. (1966) studied the effect of water-table on the growth of tomato, snap bean, and sweet corn by maintaining water-table at 15, 30, 45, 60, and 90 cm below the surface in three soil-texture classes. The investigators stated that ground water itself can not adequately characterize a drainage condition and added that soil textural and soil structure are of great importance in determining soil-water-air distribution above a water-table.

Meek et al. (1980) evaluated the effects of three water-table depths (30, 60, and 90 cm) on the growth of cotton in a field experiment. The optimal water-table for cotton was 90 cm or greater; at 30 cm and 60 cm, seed cotton yield was reduced by 43 and 25 percent percent, respectively.

In their study of the response of corn to excessive soil-water conditions at different growth stages, Kanwar et al. (1988a) found that increased soil wetness during the early part of the growing season caused poor crop growth and significantly reduced yield. In another study in Iowa, Kanwar et al. (1986) examined whether certain plant and soil measurements could be used as indicators of crop response to excessive wetness at various levels of drainage. Plant-canopy temperature seemed the best indicator of plant stress due to excessive wetness in the root zone.

Stress-Day-Index Model

The stress-day-index model was introduced by Hiler (1969) to evaluate the effects of deficient-water stress on crop yields. This concept was proposed as a quantitative means of determining the degree of stress imposed on a crop during its growing season. The same concept could be used to measure the degree of stress imposed on plants under excessive soil-water conditions. Ravelo et al. (1982) and Hardjoamidjojo et al. (1982) used this concept to characterize the drainage requirements of crops.

It is well-known that most non-forage crops are more sensitive to water stress at certain growth stages than at others. The SDI concept, developed to account for these differences quantitatively (Hiler et al. 1974), is determined under excessive soil-water conditions by using stress-day factors and crop susceptibility values for different stages of crop growth. The index is computed by the equation

$$SDI = \sum_{i=1}^{n} (SD_i \times CS_i),$$

Where n is the number of growth stages, i through n; SD is stress day factor; and CS is the crop susceptibility factor.

Ravelo (1982) used the SEW_{30} as the stress-day factor, SD, in the above equation. SD in the above equation was also used later as SEW_{30} by

Hardjoamidjojo et al. (1982) and Kanwar et al. (1988).

Hardjoamidjojo et al. (1982) attempted to determine if yield affected by excessive soil-water conditions can be related directly to a stress-day index based on SEW_{30} as a stress-day factor. Using SEW_{30} values from an Ohio study as stress-day factors, he found a strong relation between SDI and relative yield. He also tested the regression model obtained from the Ohio study data against three other sets of data, two from India studies (Joshi and Dastane, 1966; and Chaudhary et al., 1975) and one from an Iowa study (Ritter and Beer, 1969). He found that the regression model from the Ohio study was in good agreement with the results from the independent experiments, despite differences and variations in experimental conditions.

The SEW_{30} concept

The relation characterizing crop-yield response to excessive soil water is an important consideration for an optimum subsurface-drainage system for poorly drained soils of humid areas. This relationship is also essential to maximizing crop production, water use, and energy utilization (Morey et al., 1975). As discussed by Wessling (1974) and Bouwer (1974), Sieben (1964) introduced the concept of the sum of exceedance values in water level, currently known as the "Sum of Excess Water" (SEW_{30}), a value relating yield production to high-water tables. The SEW_{30} concept was originally defined as

$$SEW_{30} = \sum_{i=1}^{n} (30 - WTD_i),$$

where WTD is the daily water table depth on day i and where n is the number of days.

For this computation, negative terms were neglected, and SEW_{30} values were expressed in cm-days. Sieben (1964) observed that crop yields were essentially at maximum levels if SEW_{30} values did not exceed 200 cm-days.

Geohring and Steenhuis (1987) observed decreased yields of corn and alfalfa as SEW_{30} values increased. Carter et al. (1988) calculated SEW_{30} values annually (January-October) for eight years, for drained and non-drained areas under sugarcane crop. He reported that the installation of surface drains lowered the water tables and reduced SEW_{30} and SEW_{45} (sum of excess water 45 cm below soil surface) values during years of great rainfall. Using 40 m^2 of concrete border plots, Carter et al. (1990) imposed six treatments of excessive soil water (within 30 cm of the soil surface) for three, six, and nine days during corn vegetative and tasseling/silking stages. Both before and after treatments were imposed, the water table was maintained at or below drain depth. SEW_{30} values were calculated from the water-table data, and CS values were determined for yield data to develop the SDI and the relative yield relations for corn.

A three-year study was conducted by Kanwar et al. (1988a) to quantify the effects of naturally fluctuating water tables on growth and yield in an area in which no artificial drainage was available. Water-table data were used to calculate SEW_{30} values, which were related to grain yield, canopy height, plant population, shoot height (canopy and knuckle height), and dry-matter production. The results of these studies showed that SEW_{30} values as low as 40 cm-days in the early part of the growing season could significantly reduce corn yields. These results also showed that corn yields decreased linearly when SEW_{30} values increased. Moreover, for wet years, grain moisture content at harvest increased linearly when SEW_{30} values increased.

Evans et al. (1986) studied the effects of 10 days of surface flooding on different stages of corn. They calculated SEW_{30} values from duration of water table used for surface flooding. They also incorporated results from studies of Joshi and Dastane (1966) and Chaudhary et al. (1975) regarding short-term surface flooding to calculate SEW_{30} values. Evans et al. (1986) calculated SDI values using their own normailized crop susceptibility (NCS) values, SEW_{30} values of the two previously mentioned studies, and their own SEW_{30} values. Furthermore, they developed a relationship between SDI and relative yield.

Crop susceptibility factors

Crop susceptibility (CS) is a function of plant species and growth stage. Hiler (1969) discussed two methods for determing CS factors. The more common method was to subject the crop to a specified critical level of stress (soil-water condition) at each of the physiological growth stages, the timing of which is different for different species. The CS factor for each growth stage, as defined by Hiler (1969), is expressed as

$$CS_i = (X - X_i)/X,$$

where

X_i = Yield from stage i with excessive moisture stress,

X = yields from plots without any moisture stress,

CS_i = CS value for growth stage i.

Crop-susceptibility factors for corn and for grain sorghum were reported by Ravelo et al. (1982), whose data were based on flooding studies by Howell et al. (1976). Desmond et al. (1985) reported on the CS factors in a three-year lysimeter study of the three growth stages of soybean.

Recently, Evans et al. (1990), Mukhtar et al. (1990), and Carter et al. (1990) have also reported CS factors for corn.

Evans et al. (1990) used both lysimeters and field plots to determine CS factors for five development stages of corn and soybeans. Crops were subjected to control flooding for 10 days at a given stage of growth. Water table was maintained at 0.75 m throughout the growing season, except during flooding. Crop susceptibility values for five stages were based on four years of experimental data for corn and five years of data for soybean. These investigations concluded that corn was most susceptible to flooding at the late vegetative and flowering stages of growth, whereas soybean was most sensitive during the pod-formation and early pod-development stages. Moreover, CS values for a given crop-growth stage were different not only from soil to soil, but also from year to year. These variations were attributed in part to factors other than flooding stress, such as soil type, fertility level, and heat stress (Evans and Skaggs, 1984).

To eliminate the effect of uncontrolled factors on CS values, Evans et al. (1990) suggested the normalizing approach. They found that the normalizing approach not only made the CS factors independent of stress duration but reduced year-to-year variation. The NCS factors can be calculated as:

$$NCS_i = CS_i \;/\; \left(\sum_{i=1}^{n} CS_i \right),$$

where NCS_i is the normalized CS factor for growth stage i and where n is the number of growth stages for a crop in the growing season.

Mukhtar et al. (1990) conducted an experiment in 300 cm-wide and 600 cm-long field-type lysimeters. Each lysimeter was isolated by a plastic barrier. The soil at the site was a Nicollet loam. All treatments except the control were flooded once during the growing season for ten days at each of the four corn-growth stages (early vegetative, late vegetative, flowering, and yield formation). Flooding corn irrespective of the physiological stage of plant development reduced grain yields, but corn was more susceptible to flooding at the early and late vegetative growth stages. The investigators also presented the CS and NCS values for the four stages of corn.

Carter et al. (1990) conducted an experiment on silt alluvial soil to determine both the yield response of sweet corn to excessive soil-water conditions and the crop-susceptibility factors during vegetative and tasseling/silking stages of growth. Normalized CS factors were 0.55 and 0.45 for the vegetative and tasseling/silking stages, respectively. These investigators concluded that sweet corn is highly susceptible to excessive soil-water stress during both stages of growth, but even more so during the vegetative stage.

Ahmad and Kanwar (1989) presented a review of CS factors and stress day factors (SEW_{30}). They evaluated the effects of these factors and of their normalized CS factors on the relationship between stress-day-index (SDI) and relative yield (RY). The result of this study indicated that relations that were developed between SDI and RY by using CS factors were significantly different from those developed by using the corresponding NCS factors.

Fate of Nitrogen (N) in Soil

N-fertilizer in soil

Nitrogen in fertilizer may be found as free ammonia, urea, salts of ammonia, and nitrate. Urea and ammonium nitrate are the two most common forms. Urea which consists of 46 percent N, is commonly used as a fertilizer. In warm aerated soil, urea hydrolyzes to ammonium nitrogen in a few days. Similarly, soil bacteria convert ammonium (NH_4^+) to nitrate in a few days or weeks.

But there are important exceptions. The ammonium form persists indefinitely in flooded soils and is taken up by plants whereas when urea remains on the soil surface, much of the nitrogen is converted to gaseous ammonia and lost to the atmosphere. Volatilization also occurs in the soil through biological reduction of nitrate to nitrous oxide (NO_2). Excessive soil water can cause the loss of nitrogen by denitrification.

Plant Nutrient Behavior in Flooded Soil Conditions

Flooding the soil has a significant effect on the behavior of several plant nutrients and on the growth and yield of crops. The changes in plant nutrient availability caused by flooding are mainly due to biological oxidation-reduction processes. The layer of water over the soil surface restricts the movement of oxygen to the soil and causes microorganisms that grow only in the absence of oxygen and those that ordinarily use oxygen to metabolize other reduceable substances to carry on respiration. These biological reduction reactions and the chemical changes accompanying them critically influence nutrient behavior in flooded soils. Thus, flooded soils exhibit two forms of toxicity to plants: one caused by the oxygen demand of the reduced chemical constituents of flooded soil; the other by the reduced components of flooded soil.

The most important toxins in flooded soil are hydrogen sulfide, Fe^{2+}, organic acids, and, in cases of decompositions of plant residue, carbon dioxide. With the exception of CO_2, all these toxins are the reduced products of anaerobic decomposition processes and have two adverse effects on plants: an increase in the oxygen requirement in the root and in the root rehizosphere; and a specific toxicity to root-cell functions.

Oxygen is usually present in a layer extending from a few millimeters to 1 cm below the soil-water interface. In the flooded soil immediately beneath this oxygenated layer, the oxygen content drops sharply, with increased depth, it becomes virtually zero.

Talbot et al (1987) reported that high concentrations of Fe^{2+} and Mn^{2+} are toxic to plants and that plants inhabiting waterlogged soil use some protective mechanisms to cope with the high concentration of Fe^{2+} and Mn^{2+}. They stated however, that plants under flooded conditions leak oxygen from their root surface and oxidize the reduced form of iron and manganese before reaching the vascular system of plants. Ashraf and Mahmood (1990) studied the water tolerance of four Brassica species and found that waterlogging caused a marked reduction in chlorophyll content in all four species. An increase in iron content in both shoots and roots of the four species was also observed.

Williamson et al. (1964) studied the effects of water-table depth and flooding on the yield of millet and reported that low soil-oxygen generally resulted in reduced respiration and reduced nutrient uptake and that reduced uptake of nitrate in particular may be partially responsible for the observed reduction in yield.

Sah et al. (1989) examined the effects of soil properties, temperatures, and organic matter treatments on phosphorous (P) desorption and availability under flooding conditions. These investigations found that under flooding conditions, plant-tissue P concentration of corn was decreased at different degrees, depending upon soil type.

Sharma and Swarup (1989) found that waterlogging decreased oxygen-diffusion rate; restricted root growth; and reduced ion uptake, especially of N, P, K, Ca, Mg, and Zn; and led to greater absorption of Na, Fe and Mn. The effect of waterlogging was also relatively pronounced at high alkalinity values.

Water-Table Management Studies in Respect to Water Quality

Water-table control via controlled dual-purpose drainage/sub-irrigation systems is becoming important in the humid regions of the United States. Controlled subirrigation is an important operational mode of this comprehensive water-management system. Fouss et al. (1988) presented a list of the advantages of proper and timely control of subsurface drainage: 1) reductions in the frequency and the duration of excessive soil water in the root zone caused by rainfall, 2) prevention of the over drainage of the soil profile, 3) reduction of the need to pump subirrigation water, and 4) increases in rainfall-use efficiency. They also presented a simulation model determining and evaluating the benefits of controlled drainage in selected geographic areas.

Bouwer and Asce (1987) stated that because of nonuniform irrigation applications and preferential flow, some deep percolation water reaches the ground water quickly. Dissolved salts, nitrates, and pesticides are the main groundwater chemical pollutants.

In the last decade, a few researchers have conducted studies on the effect of water-table management practices on water quality. Both positive and negative effects have been attributed to water-table management practices (Fausey et at., 1990). Loudon et al. (1986) found that plant nutrients and soil amendments are leached from the soil by percolating water and conveyed to receiving streams. These investigations also observed that rate of concentration was probably related to tillage method.

Kanwar et al. (1985), studying the movements of nitrate-nitrogen in relation to tillage systems and fertilizer-application methods, found that a no-till plot had significantly more nitrate-nitrogen than did moldboard-plow plots after 12.7 cm and 6.35 cm rainfalls.

Many studies have shown that water-table management practices can reduce water-quality problems. Merva and Belcher (1990) observed the concentrations of nitrate, phosphorous, and potassium, in surface runoff, soil-water solution, and subsurface flow, as functions of subirrigated high-water table and subirrigated low-water table zones. Controlled drainage and high-water table conditions caused relatively low soil-water concentrations of nitrate, phosphorus, and potassium. Moreover, results of these studies were similar to those of Protasiewicz et al. (1988).

Gilliam et al. (1979) studying the effect of drainage control on nitrate presence in agricultural fields of different soils with unique drainage properties, installed riser-type water-level control structures to raise the level of water to increase denitrification during winter. Nitrate-nitrogen movement through tile lines was greatly reduced (from 25-40 to 1-7 Kg/ha) in moderately well-drained soils because of reduction in effluent volume. In moderately well-drained soils, there was no indication of increased denitrification in the field. In poorly drained soils, drainage control had no effect on the soil profile oxidation-reduction processes but nitrate-nitrogen movement through drainage ditches decreased by approximately 50 percent.

Kanwar et al. (1988b) observed that the aeration status of waterlogged soil greatly affects the availability of nitrogen. They maintained that well aerated soil combined with adequate moisture and optimal temperatures could enhance the mineralization process and thus make greater amounts of nitrogen available. Their results supported the hypothesis that high nitrate-nitrogen concentrations exist in poorly drained soil. The report concluded that more work is needed to establish the relationships between waterlogged soils and their NO_3-N levels and plant response.

Soomro and Waring et al. (1987) stated that reductions in cotton-plant growth characteristics such as canopy height, total number of leaves, leaf area, total dry matter, and total number of fruiting points with flooding was severe and may be attributable to the adverse effects of oxygen depletion and of low nitrogen supply and uptake due to anaerobic conditions during flooding.

So and Orchard (1985) found more rapid reduction in nitrate in the pots with plants than in the pots without plants under waterlogged conditions. They concluded that plants were able to take nitrate even with waterlogging conditions.

Root Behavior in Flooding Conditions

The primary functions of roots include plant anchorage, nutrient and water uptake, nutrient and water transport, and energy storage. To perform these functions, roots need a soil environment with suitable air and moisture levels, as well as required nutrients. The presence of a high-water table and its effect on other soil constituents and processes can dramatically change the root environment. A short time after waterlogging, aerobic organisms exhaust the soil's oxygen supply. The expulsion of air and restriction of oxygen diffusion leads to reducing conditions. Under such conditions nitrate is converted to nitrogen gas, nutrients are leached away, and toxic compounds are released by the incomplete breakdown of both organic and inorganic compounds. All these processes affect root growth.

Huck (1970) studied root-growth dependence on oxygen. He measured root growth while controlling the amount of oxygen in the root environment by forcing a premixed gas around the root. Root elongation ceased 2 to 3 minutes after oxygen was purged from the system, and roots were able to recover to normal growth rate when anoxic stress was imposed for less than 30 minutes. Anoxic stress lasting three hours for cotton or five hours for soybeans, however, killed roots. Two to five percent oxygen levels reduced root-growth rate, but did not kill the root. Full growth potential was realized with a gas mixture containing 10 percent oxygen.

In their rhizotron field study, Stanley et al. (1980) used two water-table heights (45 and 90 cm) to determine the effects of temporary high-water tables imposed during different growth periods on the development of the tops and roots of soybeans. Water table was established for seven days during preflowering, postflowering, and postharvesting growth periods. Root tolerance to water-table level changed as plants progressed through their growth cycle. Little damage occurred in the roots during imposition or removal of water-table treatments. During postflowering, reduced individual root tolerance, but strong total root-system adjustment, was evident.

Del Castillo (1983) showed that the ability of roots to recover is linked to plant age. Soybean roots were exposed to low oxygen for 48 hours during the preflowering vegetative stage and the postflowering prepod initial reproductive (R2) stage. The root growth of plants in the preflowering vegetative stage was reduced to 6 percent of the norm. Growth recovered to 28 and 66 percent of the norm 24 and 48 hours after normal oxygen levels were restored, respectively. The root growth of plants in the R2 stage ceased after 12 hours of exposure to low oxygen, and growth did not resume for the remaining 36 hours of the treatment. During the 48-hour recovery period, root growth remained below 21 percent of the norm.

McDanial and Skaggs (1988) conducted a study characterizing corn-root response to high-water table. Experiments in this study consisted of twelve high-water table treatments and of a control. Water was raised to the surface and completely flooded the root system for three separate durations at four different growth stages. The selected growth stages were V4 (2 weeks), V8 (4 weeks), V12 (6 weeks), and silking (8 weeks). For each growth stage periods of flooding were one, three, and five days. Both time of flooding and root depth affected root mortality rate. Flooding for three days caused a mortality rate of between 17 and 50 percent in the 0 to 0.15 m deep roots, and between 41 and 94 percent in the 0.12 to 0.15 m deep root. Five days of flooding killed nearly all roots except those in the V8 stage; only 43 and 75 percent were killed in the upper and lower sections, respectively.

McDanial and Skaggs (1988) also observed that root growth was affected by duration of flooding and by growth stage. They also found that growth rate was below 20 percent of the normal for the day of flooding, regardless of growth stage. Growth ceased when plants were flooded for more than one day during the V4, V12, and silking stages and for more than three days during the V8 stage. Normal growth rate was restored within five days for all treatments except for those in the V4 and V5 stages; these treatments required 11 days to recover.

So and Orchard (1985a) investigated the effect of flooding on both sunflower and sorghum growth during a nine-day waterlogging period under glass-house conditions. Depletion of oxygen in the soil-root environment reduced growth and root ability to absorb water. Reduced water uptake by the plant, in turn reduced growth.

Kramer (1969) suggested that transient waterlogging may reduce water adsorption directly by decreasing the permeability of roots to water, and directly by reducing the size of the root system through death or reduced root growth.

Root-Measuring Techniques

Early root studies

The study of roots has always been a difficult and tedious task. In many instances, plant roots must be isolated from the soil matrix before they can be quantified. Separation of roots from soil is a time-consuming and laborious process involving the excavation of whole plants or the collection of numerous undisturbed soil cores in the plant vicinity. After being retrieved and washed free of soil, root samples are quantified according to length, weight, or volume. The difficulties in root sampling have discouraged these studies in the past and have made them the least-studied parts of plants.

Over the years, many root-study methods have been developed, each with its own advantages and disadvantages. These methods have been classified by Kolesnikov (1971) and reported by Bohm (1979). Common methods include excavation, monolith, auger, profile wall, and glass. Historically, the excavation method has been the first and foremost method used. Improved techniques have been developed for specific root-studies, but all methods attempted have not been successful. For example, isotopes were popular for a time but later proved successful primarily in plant-physiology studies. To accommodate some of the new perspectives arising from the glass wall method of investigating roots, a technique was developed.

The glass wall method allows researchers to view the root growth of a plant throughout the growing season. The glass-wall method utilizes an underground chamber, called a rhizotron, with glass partitions erected against a soil profile. One such system is where plants are grown in a glass-sided box (Bohm, 1974).

Minirhizotron development

An early adaption of the glass wall method was suggested by Bates (1937). Citing low cost and mobility, Bates suggested using glass tubes rather than large glass-walled chambers to view roots. With the aid of a mirror and a light source, he viewed rye-grass roots as they intercepted a glass tube inserted into the soil.

Wadington (1971) used a similar method for observing the growth of wheat roots. He used acrylic tubing and a fiber-optic probe to view the roots intersecting the tube walls at various depths.

Bohm (1974) used 150 mm-long glass tubes attached with vertical and horizontal lines forming a grid section to observe the growth and distribution of radish roots in the field. He used a mirror mounted on a rod, along with a battery-operated light source, for right-angle viewing. Bohm was the first to use the term minirhizotron to describe this method of observing root growth. The mirror mounted on a rod for viewing roots on the glass walls was later replaced with a fiber-optic scope called an endoscope (Vos and Groenwold, 1983; Maertens and Clauzel, 1982).

Further research with minirhizotron was conducted by Sanders and Brown (1978) on soybeans. Square tubes were placed in the soil at a 45-degree angle, with one edge of the tube placed in the vertical plane to allow two viewing surfaces. A fiber-optic duodenoscope replaced the mirror and the magnifying glass used by Bohm. A camera attached to the fiberscope allowed photographs of the roots to be taken, thereby, reducing the time required to collect data in the field. Pictures were taken of the roots at specific depth intervals and were later analyzed for root length.

Summary of Review of Literature

The literature shows that most research conducted to determine the response of crops to excessive soil water pertains to surface flooding and that few studies have been conducted where water levels were maintained below the surface. Studies show that both crop growth and crop yield decrease when flooding duration increases. The main objective of these studies was to determine growth or yield reductions in crops flooded at various stages of growth.

Crop response to water stress for optimizing water-management system design is the most useful measure. Some studies have sought a relationship between crop yield and water stress. For instance, Sieben (1964) introduced the SEW_{30} concept, and Hardjoamidjojo et al. (1982) incorporated an approximate method based on the stress-day-index (SDI) concept (Hiler, 1969). The SDI approach is based on CS and SD factors to calculate the SDI values. Many researchers (Hardjoamidjojo et al. , 1982; Evans et al., 1990; Carter et al., 1990; Ravelo et al., 1982; Kanwar et al., 1988a) have used SEW_{30} values calculated from water table data as SD factors. These investigators have developed relationships between SDI and the relative-yield for corn. The SEW_{30} concept, developed for the winter cereal crops of the cold soils of the Netherlands, has never been tested for warmer soils and or for different positions of water tables below the surface. Thus, studies of the SEW_{30} concept are warranted for local conditions, and refinement of the concept is needed. Because soil behavior under flooding conditions is a complex issue, its study is bound to include other factors (i.e, nutrient behavior in plant and in soil both during and after flooding) affecting plant growth and plant yield.

PART 1: EFFECT OF HIGH WATER TABLE CONDITIONS ON CORN GROWTH

ABSTRACT

The effect of two water table depths (surface vs. water table at 15 cm depth) and four stress levels (equivalent to 90, 180, 270, and 360 cm-days of stress as defined by SEW_{30} concept) on corn vegetative growth was investigated in environmentally-controlled growth chambers. Canopy height, stem height, leaf area, and dry matter were compared for both water table conditions at each stress level.

All growth parameters were significantly larger for water table at 15 cm depth than for surface flooding at all four stress levels. This study indicated that SEW_{30} concept does not accurately quantify excessive-soil-water stress and its relationship to crop response. Leaf area was found to be the growth parameter most sensitive to excessive soil water and the best indicator for predicting shoot dry matter of corn. Greater dry matter yields with water table at 15 cm depth than with surface flooding suggest that better crop growth could be obtained if water tables were maintained at depths below 15-cm rather than at the surface.

INTRODUCTION

Growth and yield of crops are influenced by a number of soil and climatic factors, one of the most important of which is water. Although most crops require significant amounts of water for their growth, too much or too little water can limit potential plant-growth rates (Scott and Batchelor, 1979). Compared with the effects of deficit soil water, those of excessive soil water on plant growth, have received little attention. Nevertheless, knowledge of crop response to excessive-soil-water conditions is very important in the design of optimal drainage systems (Hiler, 1969).

Ideally, drainage systems are designed to prevent excessive-soil-water conditions from developing and to provide trafficable conditions for planting and harvesting. Research workers have recently realized that leaching of agricultural chemicals also are important factors to consider in the design of drainage systems because of the need to avoid contamination of water resources. Surface and subsurface drainage water is a major carrier of agricultural chemicals, and therefore excessive drainage is undesirable. Yet, poor drainage is also undesirable because an excessive soil-water condition in the root zone is accompanied by both oxygen deficiency and root damage if it prevails for more than a few days (Williamson and Kriz, 1970; Bradford and Yang, 1981; Williamson and van Schilfgaarde, 1965). In Iowa, Kanwar et al. (1983,1984) found that inadequate drainage systems were responsible for average corn-yield reductions equal to 32% of maximum production potential and that, on poorly drained soils, 100% crop-production losses were expected in 4 out of 10 years. Thus, before designing a drainage system for a crop or cropping system in a given area, we need to know the response of the crop or crops to excessive water. Furthermore, drainage systems should not only remove excessive soil-water, but should also reduce leaching of agricultural chemicals into water supplies.

Water-table depth is an important parameter in the drainage system design that affects crop growth (Wesseling, 1974). Because maintaining a constant water-table depth in an agricultural field for a period is difficult, most studies examining crop response to high water-table conditions have been conducted using field-type lysimeters (Hiler and Clark, 1971; Cannell et al., 1980; Mukhtar et al., 1990; Evans and Skaggs, 1984). In some studies, lysimeters have been provided with moveable shelters to protect them from undesirable weather, especially from rainfall (Cannell et al., 1980; van Schilfgaarde and Williamson, 1965). In other studies (van Schilfgaarde and Williamson 1961, 1965) lysimeters were placed in growth chambers to control environmental conditions and to reduce the variability in plant growth encountered in field lysimeters.

Many studies have been conducted to determine the response of crops to different high water-table conditions. Fausey et al. (1985) found that flooding at the germination stage of corn can significantly reduce emergence. A number of studies conducted to determine corn susceptibility to high water tables at different stages of growth have concluded that the greatest crop damage and the maximum yield reduction occur during the early vegetative stages of corn (Joshi and Dastane, 1966; Kanwar et al., 1988; Mukhtar et al., 1990; Ahmad and Kanwar, 1989; Singh and Ghildyal, 1980; Chaudhary et al., 1975; Ritter and Beer, 1969) or the late vegetative stages (Evans and Skaggs, 1984; Evans et al., 1986). Studies have also been conducted where static water tables were maintained at different depths below the soil surface during the entire growing season (Hiler and Clark, 1971; Williamson and Carreker, 1970). Still other studies examined the response of crops to transient water table conditions (Cannell et al., 1980; Tondrue et al., 1976). Sieben (1964) introduced the concept of the sum of the exceedence value in excess soil water, now known as the "Sum of Excess Water" (SEW_{30}), which relates yield reduction to the occurrence of a high water table within 30 cm of the soil surface. Few studies have been conducted to investigate the effect of excessive water (due to surface flooding or due to water table below the soil surface) on the sensitive stages of crops, and almost no study has been conducted to distinguish between desirable and undesirable excessive water with respect to duration of flooding and depth of water table in the root zone. Therefore, a study was conducted in controlled environment chambers with the following objectives:

1. to determine the effect of two water table positions (at the soil surface and 15 cm below the soil surface) on corn growth during the vegetative stage, with four different flooding durations; and

2. to determine an optimal SEW_{30} value for maximum corn growth under a given set of fertility, temperature, and soil-type conditions.

EXPERIMENTAL PROCEDURE

Growth Chambers

To determine the effect of excessive soil water conditions on the response of corn, two controlled-environment growth chambers (Conviron PGW36[1]; 243x243x121 cm) were used. Growth chamber temperatures were programmed to simulate normal mid-Iowa temperatures between May 8 and June 29. Daily diurnal temperature patterns were based on the 30-year normal maximum and minimum temperatures for the corresponding dates and temperatures were ramped between hourly set points. During the 16-hour daylight period, light was provided by 45 incandescent 120-W and 30 fluorescent 115-W light bulbs, except for the first and last hour, for which only incandescent light and only fluorescent light were provided, respectively. Relative humidity was maintained at 70 percent.

Construction of Lysimeters Used in the Growth Chambers

Eighteen plastic containers (40x65x81 cm) were utilized as lysimeters in the growth chambers. A hole (about 2.50 cm diameter) was made at 5 cm from the bottom of the container with a power saw (Figure 1). This hole was fixed with a bung crossing the container wall on both sides and providing a watertight seal. To raise or lower the water in the container, a 5 cm diameter perforated plastic pipe was connected by plastic coupling to the bung. The outside of the bung was fitted with a

[1]Reference to a trade or company name is for specific information only and does not imply approval or recommendation of the company or product by Iowa State University to the exclusion of others that may be suitable.

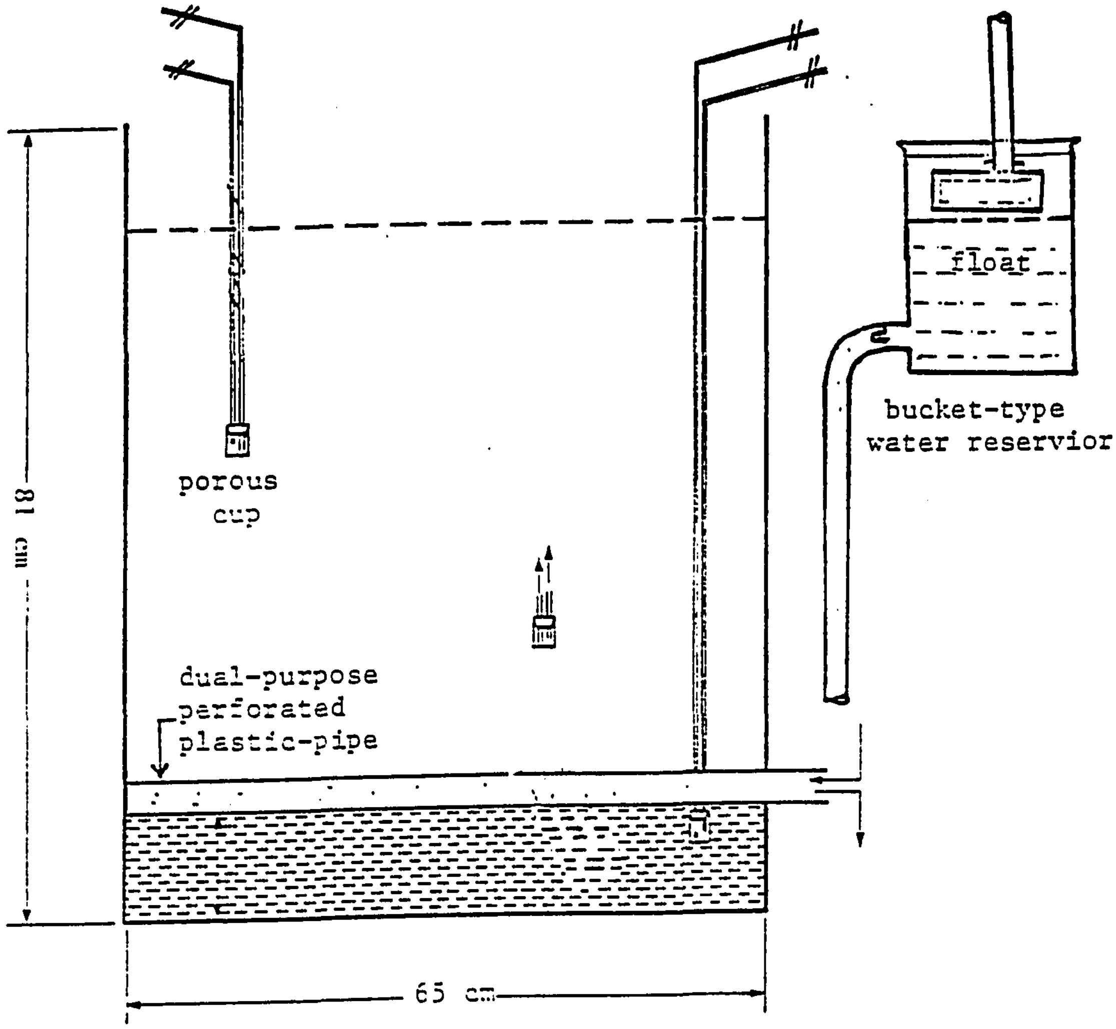

Figure 1. Schematic diagram of the lysimeter (with water table maintenance facility) placed in the growth chamber

garden-hose barb, which was connected to a float system and a water supply reservoir by a transparent polyvinyl tube. The float system consisted of a small bucket-type water reservoir and a float. The system was portable, and was used to change the water level inside the container by changing its height on a steel shelf, which could be adjusted according to the needs of the study. A set of solute suction cups was installed (to take soil water samples) at depths of 0.20 m, 0.40 m, and 0.60 m in each of the lysimeters at the time of soil placement. A plastic tube 0.30 m deep and 2.54 cm in diameter was installed in each lysimeter to measure internal water elevation.

Placement of Soil in the Lysimeters

Eighteen lysimeters were filled with a Nicollet loam soil from the Clarion-Nicollet-Webster Soil Association. Some of the physical properties of this soil are given in Table 1. A small area (6 m x 6 m)

Table 1. Particle-size distribution, gravel percentage, and soil reaction of Nicollet loam soil (from Charkhabi, 1990)

Hor	Depth cm	Sand %	Fi.silt %	Co.silt %	Clay %	Gravel[a] %	pH_w[b] %
Ap	0-15	29.5	11.3	33.0	26.2	0.1	5.9
A1	15-25	28.7	13.1	32.1	26.1	0.4	6.1
A2	25-46	31.5	17.2	23.2	28.1	0.2	6.6
AB	46-56	34.4	10.8	27.4	27.4	1.1	7.0
Bw	56-76	38.6	9.2	24.9	27.3	2.2	7.1
BC	76-86	31.0	11.8	32.5	24.7	1.9	7.2
C1	86-102	40.1	10.8	26.8	22.3	3.0	7.7
C1	102-117	38.2	12.0	30.2	19.6	2.0	7.8
C1	117-135	39.2	11.8	29.1	19.9	2.2	8.0
C2	135-160	38.6	12.6	29.0	19.8	1.5	8.1

in the field was selected, corn residue was removed, and divided into 18 smaller areas (2 m x 1 m), one for each lysimeter. The soil profile of each smaller area was excavated in 0.20 m layers, to a depth of about 0.80 m. Then the 0.20 m soil layers were repacked inside the lysimeter to match the original vertical soil profile and bulk density. Surplus soil, if any, from the surface was saved for later use after settling. Lysimeters filled with soil were brought back to Iowa State University and placed in growth chambers. Nine lysimeters or one replication could be placed in one growth chamber at a time (Figure 2). To allow the soil to settle, water was raised from the bottom of the lysimeters to the top of each lysimeter and was kept there for three days. Soil in almost every lysimeter settled during this flooding event. The lysimeter was then refilled with the surplus soil to bring the depth of the soil in the lysimeters to the depth of the original soil excavation. The same soil was used for two growth chamber runs.

Experimental Design and Layout

This experiment included eight treatments plus a control. The control had a water table maintained at the 70-cm depth. The eight treatments consisted of two water table positions (surface and 15 cm below the soil surface) each at the same four excessive water stress levels. The same level of excessive wetness stress (Sieben's SEW_{30} concept) was applied by maintaining water at the two different water table depths, 0 and 15 cm, for different number of days. After the specified number of days water was drained and a water table was

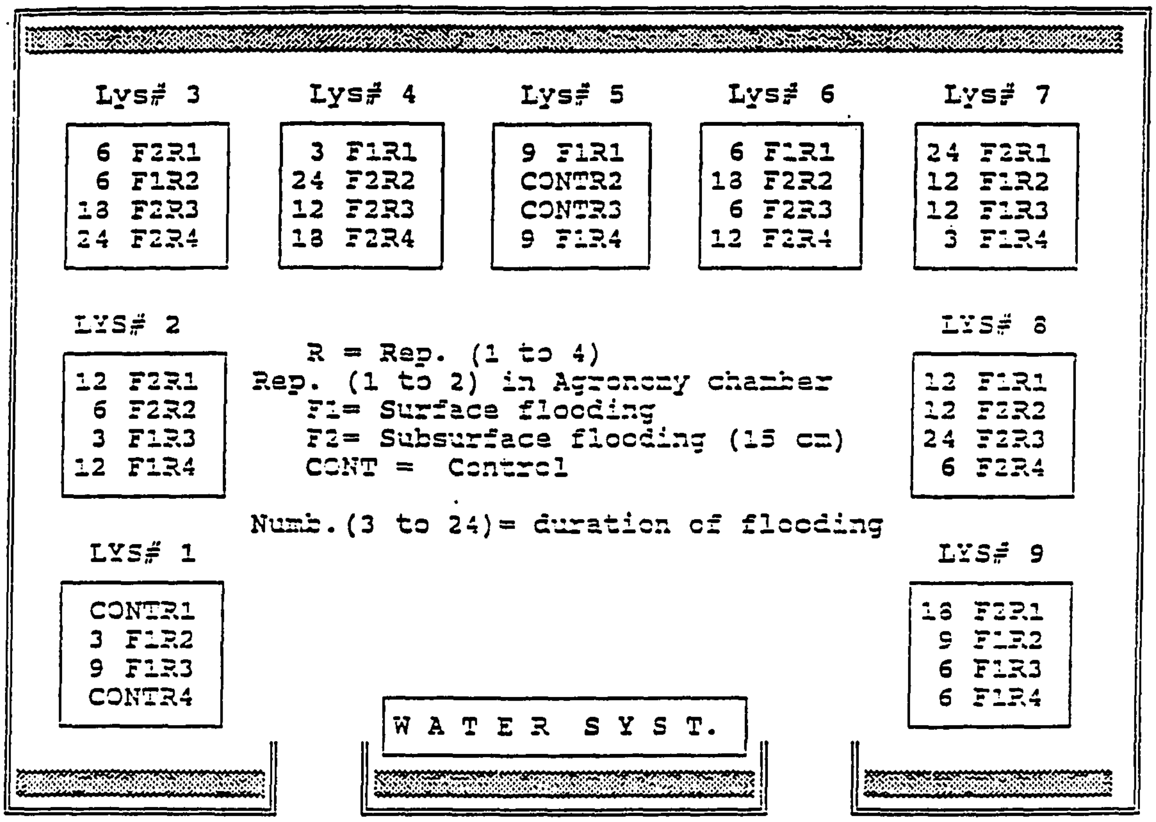

Figure 2. Layout of lysimeters and treatments in the growth chambers

maintained at the 70-cm depth for the rest of the period. Sieben (1964) used SEW_{30} concept to quantify the stress due to excessive wet soil conditions as

$$SEW_{30} = \sum_{i=1}^{n} (30 - WTD_i),$$

where WTD is the daily water table depth on day i, and N is the number of days. For this computation, negative terms are neglected, and SEW_{30} values are expressed in cm-days. Each of four treatments for the 0 and 15-cm water table depths is shown in Table 2.

Table 2. States of water-table treatments

Duration of Stress due to excessive wetness (days)	Depth of Water Table beneath the Soil (cm)	Stress Levels in SEW_{30} Values (cm-days)	Total Stress Level in SEW_{30} Values (cm-days)
Surface flooding treatments			
3	0	30	90
6	0	30	180
9	0	30	270
12	0	30	360
Water table at 15 cm below the soil surface			
6	15	15	90
12	15	15	180
18	15	15	270
24	15	15	360

The experimental design was a randomized complete block design with four runs, two in each growth chamber. Each run was consisted of a single replication. Lysimeters were arranged in the growth chambers in such a way that each received similar light levels. Figure 2 shows the layout of the lysimeters and water system in the growth chamber.

Planting

Seed bed preparation consisted of four small grooves (3x3x8 cm) being made in each lysimeter, which were about 10 cm from the walls and 20 cm apart. After planting, these grooves were filled with a potting mixture. The reason for using the potting mixture was to obtain uniform germination and to avoid crust development as a result of the frequent need for light irrigations in the growth chamber. Sixteen corn (Pioneer 3751) seeds were planted in each lysimeter, four in each groove. After germination these were thinned to six plants per lysimeter. The procedure was repeated for all plantings in both growth chambers. Each lysimeter received fertilizers at a rate of 200 kg N (8.42 gm urea per lysimeter); 60 kg P (5.50 gm superphosphate per lysimeter), and 60 kg K (2.33 gm potassium chloride per lysimeter) per hectare during the second week after planting. In all of three runs in each growth chamber, fertilizers were dissolved in 500 ml water, and solutions were evenly applied to top soil surface of each lysimeter.

Irrigation

Prior to the beginning of the experiment, soil moisture status in the lysimeters was determined by taking a set of soil samples from depths of 0-7.5, 7.5-15, 15-30, 30-45, and 45-60 cm for each of the lysimeters. Soil moisture content was at field capacity at 30 to 45 cm and was saturated beyond 45 cm. To determine a schedule for surface irrigation of lysimeters before and after water table treatments were imposed, the moisture content of the top 30 cm of soil was measured periodically during test runs in both growth chambers. The irrigation schedule was devised to rewet the upper 30 cm of soil to field capacity whenever 50% depletion of available soil water occurred. Although surface irrigation was applied, the record of daily filling of water reservoir (to maintain the required water table position in each lysimeter) showed that the plants obtained most of their water requirement from the subsurface water, except during the first three weeks. The values for the field capacity (35%) and the wilting point (13%) on weight basis were obtained from field samples.

Data Collection

Canopy height, stem height, leaf area, and shoot dry matter were measured for all water table treatments and for the control lysimeter. Water table treatments were initiated at the sixth leaf stage of corn, about 26 days after planting and 21 days after germination.

On the day before the water table treatments began, two plants out of six were harvested for dry matter and leaf area measurements. Canopy and stem heights for the four remaining plants were also measured before treatment. Canopy height and stem height were measured every third day for the first twelve days after treatments were imposed and then every six days for rest of the experiment. Plants were harvested at 53 days after planting when plants in the control lysimeters began touching the top of the growth chamber. Leaves of each plant were removed from stem to measure the leaf area using the leaf-area meter. Then both the stem and leaves were put into a paper bag and dried at 60 ^{0}c until constant weight was achieved for shoot dry matter. All results were analyzed using an analysis of variance for the complete block design.

RESULTS

Shoot Dry Matter Yield

Figure 3 illustrates the relation between SEW_{30} stress values and shoot dry-matter yield for both water table positions. For the purpose of comparison among stress levels at the two water table positions, controls were not included in the analysis of variance because they represented a zero level of stress. Both water-table levels had a significant effect on dry matter production (Table 3). Surface flooding, however, caused greater reductions in shoot dry matter than water table at 15 cm below the soil surface. When water table was maintained at surface, shoot dry matter decreased significantly as duration of flooding increased between 3 (SEW_{30} = 90 cm-days) and 9 days (SEW_{30} = 270 cm-days), but no significant decrease was observed between 9 and 12 days (SEW_{30} = 360). When the water table was at 15 cm below the surface, shoot dry matter decreased as duration (water table) increased between 6 (SEW_{30} = 90 cm-days) and 12 days (SEW_{30} = 180 cm-days), but did not decrease significantly between 12 and 24 days (SEW_{30} = 360 cm-days). Additionally, shoot dry matter responded very differently to the two water level, even at the same SEW_{30} stress levels. For example, at an SEW_{30} stress level of 360 cm-days, shoot dry matter of plants with the water at the 15-cm depth were three times as great as the dry matter of plants with the water table at the surface. Obviously, the SEW_{30} concept does not accurately describe excessive water stress as it relates to vegetative growth. Similar observations were made by Carter et al.

(1988), who obtained almost the same yield at the two different values of SEW_{30} (838 and 134 cm-days).

The percentages of shoot growth reduction[2] resulting from each of the eight treatments in relation to the control treatment were calculated. Figure 4 shows the relationship between the average shoot-growth reduction at various SEW_{30} values for each of the treatments. Shoot growth reduction increased with the durations of flooding when water table (3-cm) was maintained at the surface . Other researchers have observed similar surface flooding effects on growth reduction. (Bhan, 1977; Joshi and Dastane, 1966; Oosterhuis et al., 1990; Mason et al., 1987). Figure 4 also shows that the range of shoot dry matter reduction was greater for the surface water table treatment (82.32-40.82 = 41.50%) than for the water table at 15 cm below the surface (33.79-24.47 = 9.32) even though water table duration was greater for the later. The shoot growth reduction (40.82%) resulting from three days of maintaining a surface water table, the minimum stress imposed under this water level (SEW_{30}= 90), was much greater than that resulting from six days of maintaining a water table at 15 cm (SEW_{30}=90), which was only 24.03%.

To examine the effect of the SEW_{30} on the shoot dry matter of corn, regression models were developed. Corn shoot-dry matter decreased linearly with the increases in SEW_{30} values at both water levels (figure 5). Because the shoot-dry matter reduction for each successive increment

[2]PGR = (1-(Growth/trts.)/(Growth (cont)) x 100
Growth = (shoot dry weight (after trts. - before trts.))

of stress (90 cm-days) was greater for surface flooding than for water table at 15 cm below the soil surface, the slope of the regression line for surface flooding (0.0831 gm per cm-day) was greater than that for water table at 15 cm below the soil surface (0.018 gm per cm-day). The analysis of variance indicated that these slopes are significantly different.

Leaf Area

The first response of corn plant to excessive wetness stress was a change in leaf vein color from light green to purple. Additionally, this color change was greater on old than on young leaves. Leaf area responses were very similar to those of shoot dry matter. Leaf area decreased with the duration of both water table levels, but more so for the surface flooding. Leaf tips turned brown under longer periods of high water level, especially with the surface flooding. Reduction in leaf size, both in terms of length and width, rather than leaf number caused differences in total leaf area.

Figure 6 presents the relationship between SEW_{30} and leaf area response at the two water positions. Leaf area responded differently to the four SEW_{30} stress levels for each water table position (Table 3). These result further negate the SEW_{30} concept.

Percentage decrease in leaf area relative to control was also calculated. The relationship between average leaf area reduction and various SEW_{30} values for each treatment are shown in Figure 7. Leaf area reduction increased with the duration of both water table positions. The range in percentage reduction was greater for the surface water table (68.68 - 19.64 = 49.04%) than for the subsurface when water table was maintained at 15 cm below the soil surface (23.3 - 8.75 = 14.55%).

To examine the corn leaf area at the two water table positions, regression models for leaf area versus stress levels are shown in Figure 8. The models indicate a better fit of SEW_{30} stress values to leaf area at surface flooding than water table at 15 cm below the soil surface. Leaf area responded very differently to the water table positions at same SEW_{30} stress levels. Additionally, analysis of variance indicated that the slope of models are significantly different.

When water table was maintained at the surface, leaf area decreased significantly among all four stress values. When the water table was maintained at 15 cm below the soil surface, leaf area decreased as duration of water table between 6 (SEW_{30} = 90 cm-days) and 12 days (SEW_{30} = 180 cm-days), but did not decrease significantly between 12 and 24 days (SEW_{30} =360 cm-days). The $LSD_{0.05}$ analysis indicated that leaf area of plants for 3 days of surface water table (SEW_{30} = 90 cm-days) and 12, 18 and 24 days of the water table at 15 cm below the soil surface (SEW_{30} = 180, 270 and 360 cm-days, respectively) resulted in no significant differences. These results indicate that the SEW_{30} concept is an incomplete method to express the wetness of soil and its relationship to crop growth response.

Canopy Height

The first set of canopy-height measurements were taken on the day before water-table treatments were begun about 25 days after planting. The analysis of variance shows that treatments had a significant influence on the height of the corn plant (Table 3). Figure 9 shows the relationships between canopy height at final harvest and different levels of stress at two water table positions, including that of the control. With surface flooding, canopy height decreased sharply when stress levels increased. The canopy-height difference (63.33 cm) between 3 and 12 days (SEW_{30} = 90 and 360 cm-days) for surface flooding was about two times greater than that (22.85 cm) between the 6 and 24 day (SEW_{30} = 90 and 360 cm-days) for water table at 15 cm below the soil surface. Figures 10 and 11 show the relationship between canopy height and days after planting for surface flooding and water table at 15 cm below the soil surface, respectively. Compared with the control, both water level treatments reduced canopy height; but the effect was more pronounced for the surface flooding. Additionally, a greater range could be seen in canopy heights for all four stress levels of surface flooding compared with those for water table at 15 cm below the soil surface.

Stem Height

Stem-height measurements were made according to the same schedule as that for canopy height. Because of the slow rate of stem growth, stem height did not show any abrupt sign of stress, but longer periods of stress reduced stem height and shoot dry matter. Stem height data showed that surface flooding for longer durations (6, 9, and, 12 days) had greater reduction of stem height than that of water table at 15 cm below the soil surface. Figure 12 shows a relationship between the SEW_{30} values and stem height at the time of harvest, 53 days after planting. The maximum stem height (84.56 cm) was measured for no stress (control), followed by 82.14 cm and 74.24 cm for the six days of water table below the soil surface and for three days of surface flooding, respectively. Analysis of variance indicates that the two water tables as well as SEW_{30} values had significant effects on the stem height. Figures 13 and 14, drawn between stem height and days after planting for surface and water table at 15 cm below the soil surface, indicate that reduction in stem height under each treatment was different and that this difference was significant for surface flooding. At harvest, it was noticed that plants under surface flooding had weaker stems than did plants under water table at 15 cm below the soil surface.

DISCUSSION

Reduction in shoot dry matter for all four durations of flooding was observed at the two water table positions (0 cm and 15 cm beneath the soil surface). A greater reduction in dry matter was obtained with surface than with water table at 15 cm below the soil surface. Moreover, reduction in shoot-dry matter increased with SEW_{30} at both water levels (i.e., 90 to 360 cm-days), but shoot-dry matter reduction for each successive increment of stress (90 cm-days) was significantly greater for the surface flooding than for water table at 15 cm below the soil surface. These results clearly indicate that the SEW_{30} concept fails to predict shoot-dry matter accumulation accurately because the concept gives equal value to stress from different water table levels of different durations. The SEW_{30} concept could be improved by dividing the wet stress-zone (30 cm) into two subzones and developing crop response dry-matter yield and other growth parameters versus SEW_{30} values for each subzone.

The other growth parameters measured in this study were leaf area, canopy height, and stem height. A greater reduction was observed in shoot dry matter than in leaf area relative to the control for the same values of SEW_{30} at two water table positions. Relative to canopy height, leaf-area data showed wet-stress effects very similar to those of shoot dry matter. Truman et al. (1966) also found that leaf area was in direct proportion to the total dry weight of the plant at harvest, because leaf-area reduction reflects the reduction in photosynthetic activity in plant and because dry matter depends upon photosynthesis. This study suggests the development of stress-effect measurements using plant leaves in situ as an alternative to methods requiring researchers to wait for yield or to harvest plants before maturity. This can be done by developing relationship between stress levels and leaf area or leaf characteristics (chlorophyll or photosynthesis), and between leaf area or leaf area characteristics and Yield. Canopy height and stem height responded to excessive stress similarly. Change in canopy height after removal of stress was a good indication of plant survival. No plants died under either water table level or under any duration of stress imposed. All growth parameters, (i.e., shoot dry matter, leaf area, plant and stem height) halted under long surface flooding treatments but not under water table at 15 cm below the soil surface treatments. When results of these growth parameters are compared with those of shoot dry matter, it can be seen that leaf area was a better representative of dry matter yield than was either canopy height or stem height. These results are consistent with Scott et al. (1989). They found that dry matter reductions due to prolonged flooding were greater than those found for canopy height for soybean. A rapid increase in canopy height, coupled with a weak stem after stress, especially for long duration of surface flooding (i.e., 6, 9, and 12 days) did not result in a close correlation between canopy height and dry matter yield. These results indicate that leaf area might be a good alternative measurement for determining the effect of excessive wet stress on the shoot dry matter of corn.

SUMMARY

An experiment was conducted in two environmentally controlled chambers to evaluate the effect of two water table positions and different stress levels (SEW_{30}) on the response of vegetative stage of corn. Eighteen plastic containers (80 cm x 65 cm x 40 cm) were used as lysimeters in growth chambers. A water-supply system was built to raise or lower water tables inside each lysimeter as needed. Plant measurements such as canopy height, stem height, leaf area, and shoot-dry matter were obtained and compared at both water levels and all stress levels. This study resulted in the following conclusions:

1. Two water table depth treatments resulted in different amounts of plant growth even at the same SEW_{30} values. This result indicates that SEW_{30} concept does not adequately predict crop accumulation for different water table depths. Two regression equations are presented, one for each water table position, which characterize dry matter accumulation for a given SEW_{30} value for the conditions of this experiment.
2. All plant measurements showed the effect of excessive wetness stress. Leaf area, however, was found to be most sensitive to excessive soil water and the best indicator for shoot dry-matter yield predictions.
3. The increase in shoot dry matter resulting from maintenance of the water table at 15 cm beneath the soil surface suggests that similar studies should be conducted to develop practical methods of

improving yield under poorly drained conditions with the use of subirrigation concept.

Table 3. Analysis of variance

Source of variation	Degree of freedom	Variables			
		Shoot Dry matter	Leaf area	Plant height	Stem height
		(mean square)			
Growth chamber	1	14.44	9244.60	1040.25**	1499.46**
Rep. (chamber)	2	0.19	117325.87	27.48	51.03
SEW_{30}	3	298.62**	4334633.05**	1558.64**	844.33**
H2Olev	1	2633.06**	16931813.46**	2884.21**	650.25**
SEW_{30} X H2O lev	3	114.49**	1181658.25**	451.47**	40.58
Error	21	47.28	36830.85	72.48	48.74
Total	31				

**significant at .01

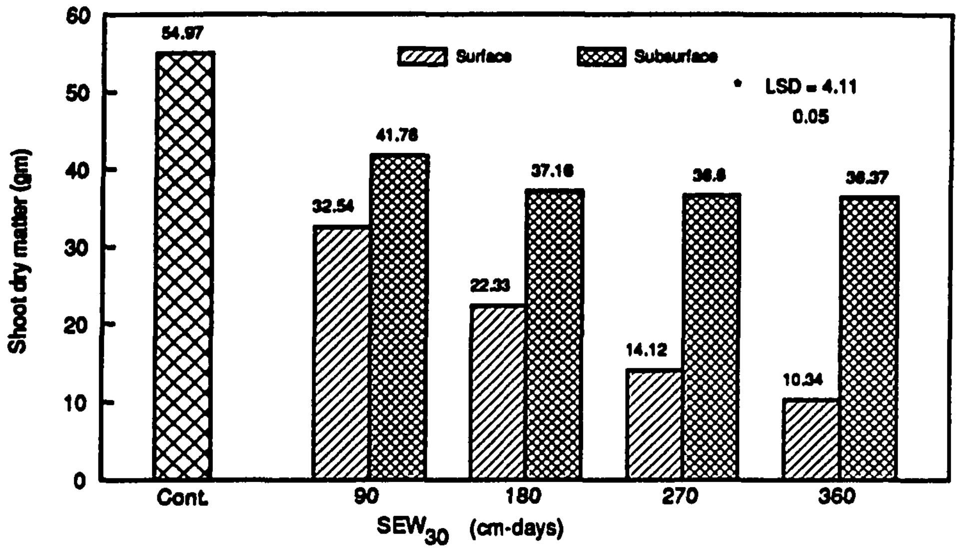

Figure 3. Shoot dry matter as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

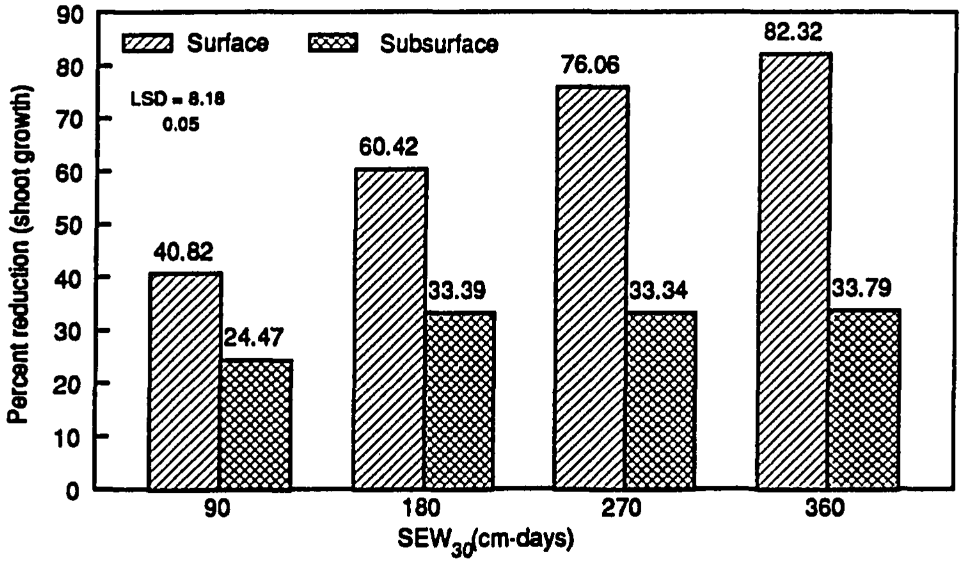

Figure 4. Percentage shoot growth reduction in relation to control as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface).

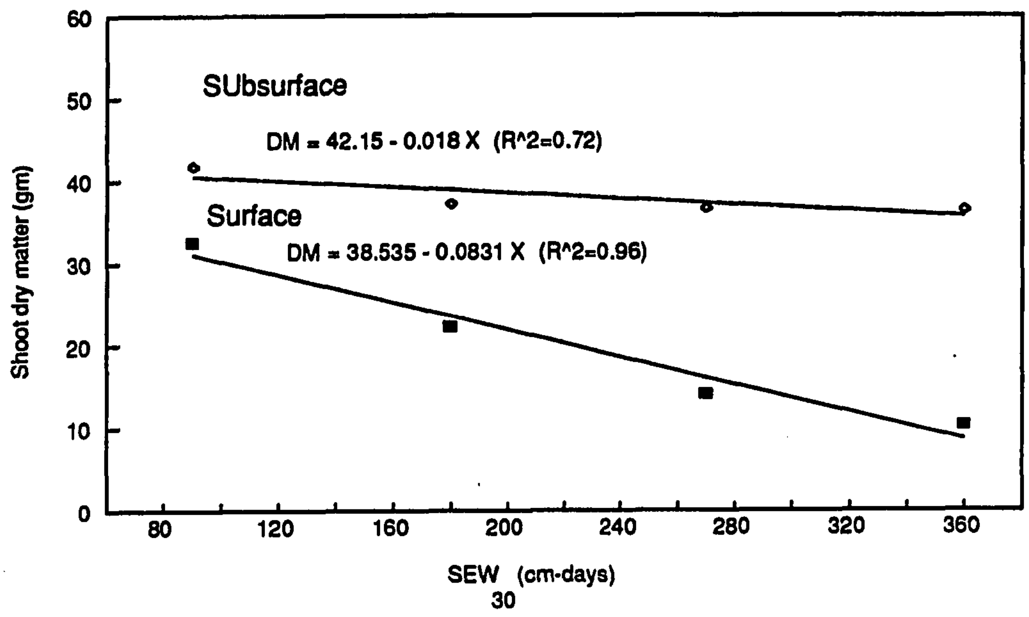

Figure 5. Linear regression models for dry matter production as a function of SEW_{30} and water table positions

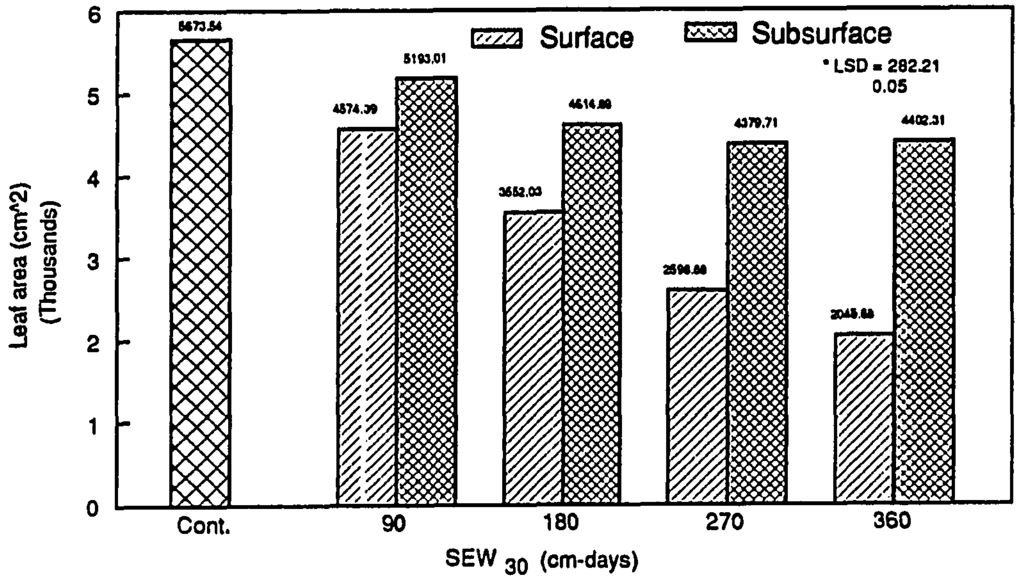

Figure 6. Leaf area (cm^2) as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

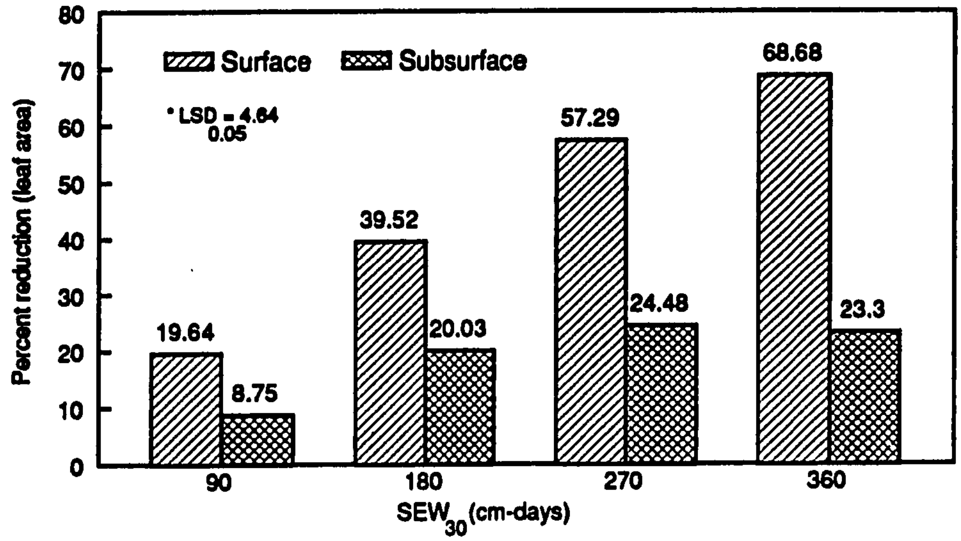

Figure 7. Percentage reduction of leaf area in relation to control as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

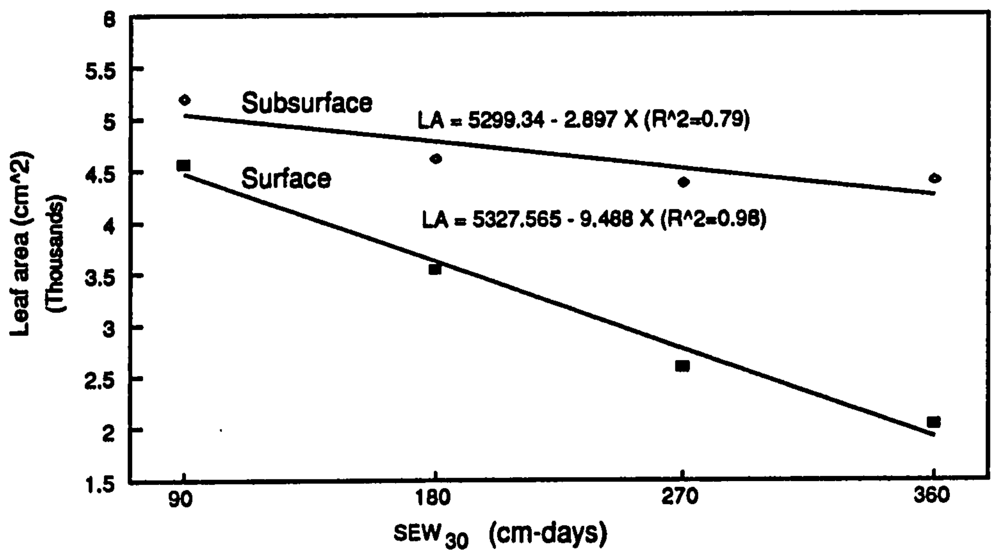

Figure 8. Linear regression models for leaf area (cm^2) as a function of SEW_{30} and water table positions

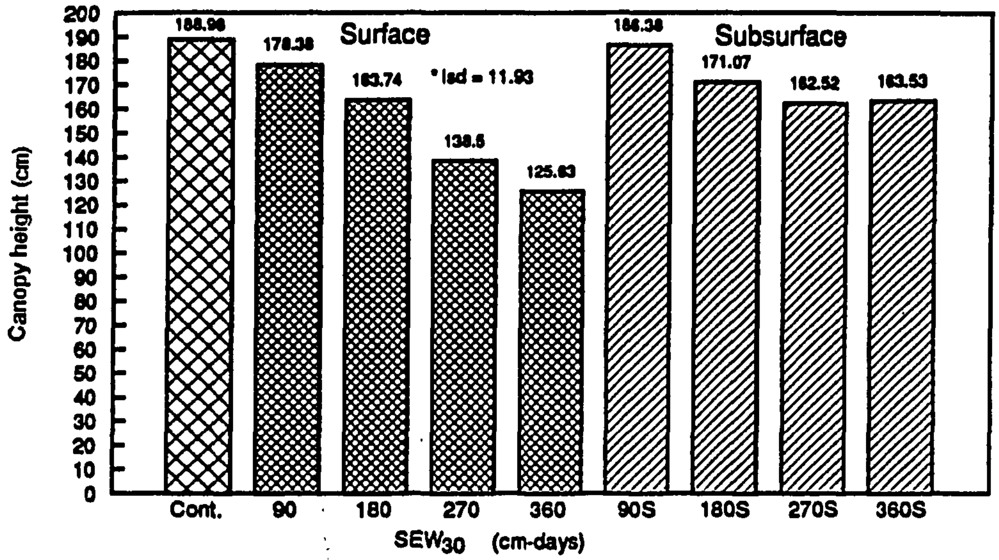

Figure 9. Canopy height (cm) at harvesting as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

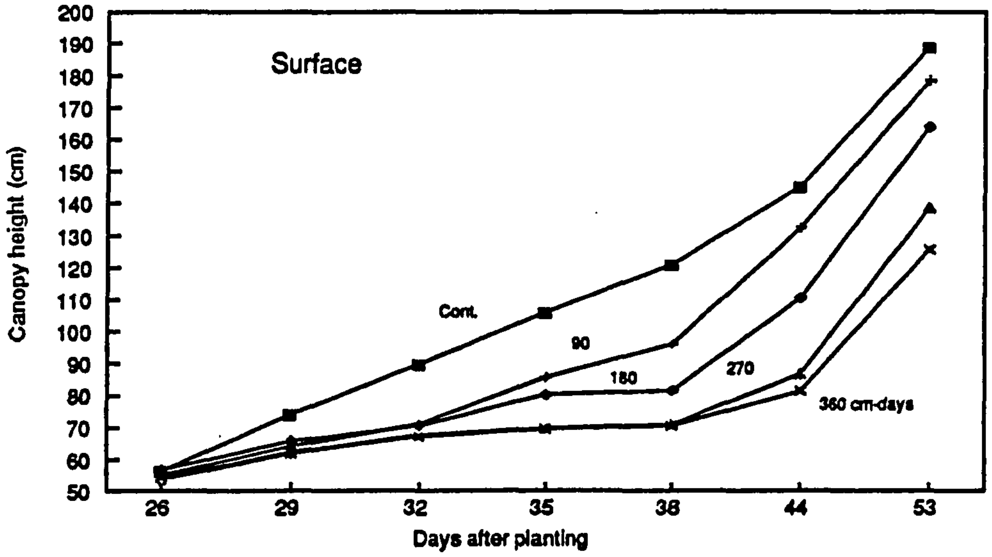

Figure 10. Canopy height (cm) at harvesting as a function of SEW_{30} (surface flooding) and days after planting.

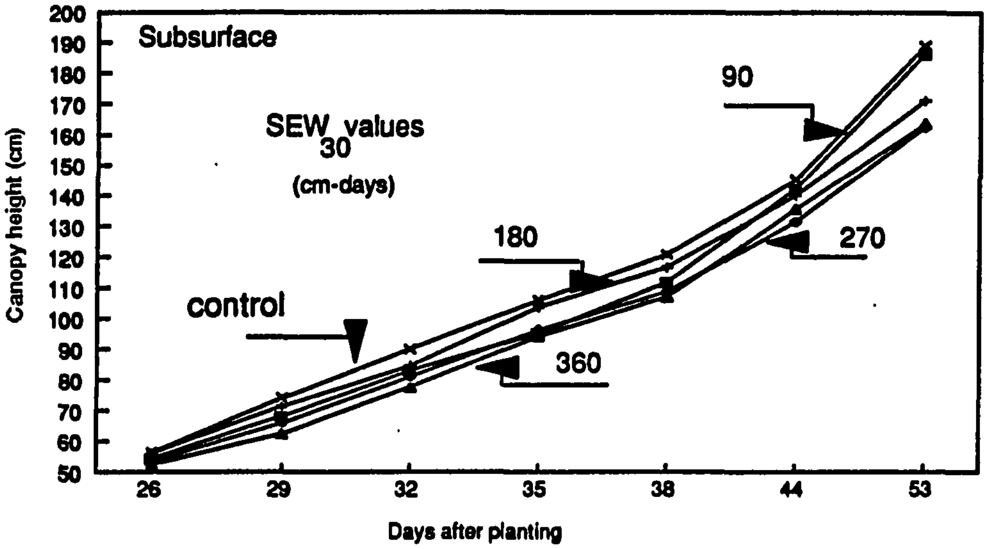

Figure 11. Canopy height (cm) as a function of time and SEW_{30} water table at 15 cm below the soil surface

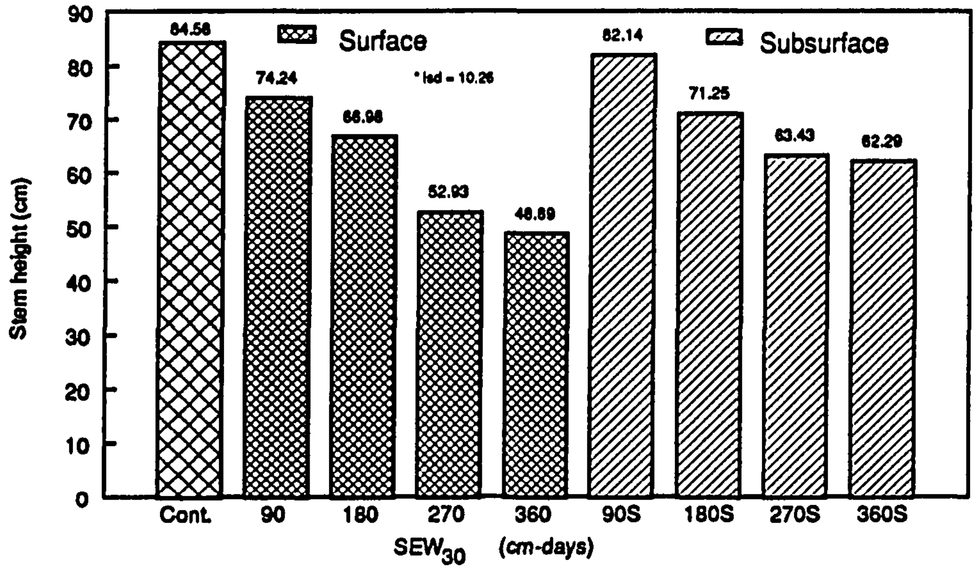

Figure 12. Stem height (cm) at harvesting as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

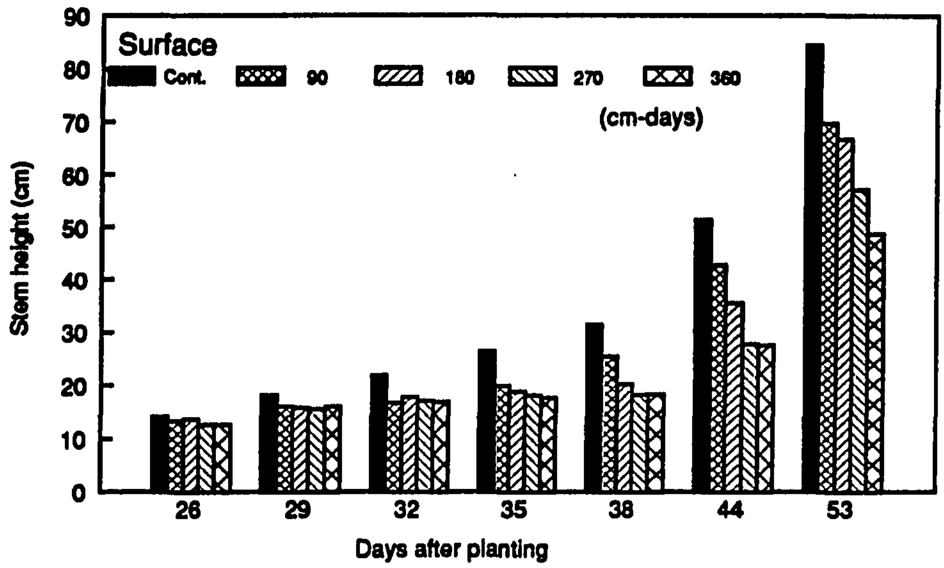

Figure 13. Stem height (cm) as a function of time and SEW_{30} (surface flooding)

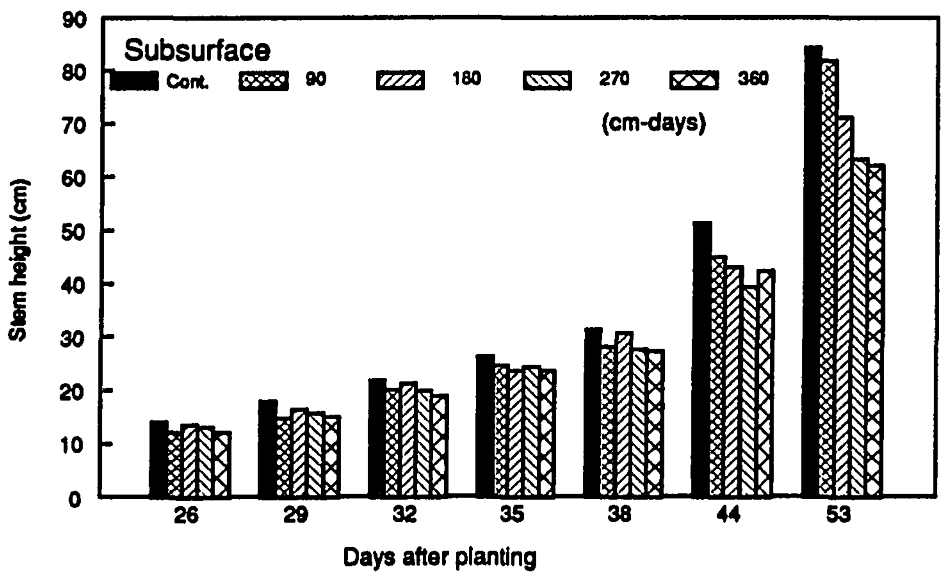

Figure 14. Stem height (cm) as a function of time and SEW_{30} (water table at 15 cm below the soil surface)

PART 2: EFFECT OF SHORT- AND LONG-TERM FLOODING ON ROOT GROWTH IN GROWTH CHAMBER

ABSTRACT

A study was conducted in environmentally controlled chambers to determine the effect of four different durations of surface flooding (when water table was maintained at the surface for 3, 6, 9, and 12 days) and below the surface (when water table was maintained at 15 cm below the surface for 6, 12, 18, and 24 days) on the growth and distribution of corn roots. To determine the effect of flooding, root growth was monitored at three depths (15, 30, and 45 cm) by the use of fiber optics and camera. At the end of the experiment, all lysimeters were cut open and the soil was washed to expose the roots. The data on quantitative measurement of roots showed that dry weight of roots decreased significantly with increased duration of flooding. Surface flooding treatments had a more damaging effect on root growth. The results of this study also showed that root length and root weight increased when the water table was kept at 15 cm below the soil surface in comparison with surface flooding.

INTRODUCTION

Roots are the major organs of plants and supply water, minerals, and substances essential for growth. If roots are damaged and become less functional, top growth will likely not occur. Vigorous root growth needs a vigorous root environment, i.e. adequate amounts of air, water, and minerals. The most important factor in the root environment is of course water. Excessive soil water in the root zone restricts growth of the root, rendering plants more susceptible to various diseases, nutrient deficiency, and toxicity. The major cause of these problems is the lack of oxygen brought about by high water table conditions. Excessive water disrupt in root metabolism, reduce root growth, or even cause root death, which results in water and nutrient stress to plants (Kramer, 1969; Leyshon and Sheard, 1974). Because excess water in the root zone creates an undesirable root environment, and because studies of crop response to high water tables have shown a reduction in crop yield (Joshi and Dastane, 1966; Ritter and Beer, 1969), it is imperative to drain excess water. On the other hand, saving soil water for drought conditions, improving rainfall-use efficiency and minimizing nitrogen losses are also very important; over-drainage is not required. Therefore, understanding root susceptibility to excessive water can be a good approach to determine the level of wet stress tolerable for a crop, based on duration and depth of the water table. Root tolerance is defined as the ability of the root system to withstand, or adjust to, the condition caused by the imposed water table (Stanley et al., 1980).

Compared with that on other plant parameters, research on root response to excessive soil water is scarce because roots are not visible and root study techniques are either laborious and/or expensive. To make root study simpler, a number of techniques were developed in the seventies. Waddington (1971) viewed wheat roots to a depth of 50 cm by using a rigid fiber optics system and plexiglass tubes; he drew what he observed. Bohm (1974) made a minirhizontron consisting of 150 mm long plexiglass tube with a movable mirror and a light source for viewing the roots. He counted the number of roots that could be seen in a 50-by-50 mm area on the wall of the tube and concluded that his method could be used under field conditions. Sanders and Brown (1978) used a fiber-optics technique for measuring and recording soybean root-systems. They concluded that their technique permits the observation and recording of the root system throughout the growing season. Recently, Upchurch and Ritchie (1983, 1984) reported on a new system for making root observations. Their system involved the lowering of a small video camera and optics system into a 51 mm (inside diameter) clear, acrylic tube, buried in the soil, and measuring the root intersecting the tube on the video monitor. Some studies have been conducted to determine the effect of temporary water tables on the rhizotron. Stanley et al. (1980) conducted a study to determine the effect of temporary water tables on top and root development of soybean in an underground root-observation laboratory. McDanial and Skaggs (1988) studied the effects of 0, 1, 3, and 5 days flooding on corn roots in acrylic cylinders.

Because root damage is the cause of shoot reduction, research is needed to study the root response to excessive water at various stages of corn for improving the design of drainage systems. Therefore, a study was conducted in environmentally controlled growth chambers to observe the qualitative and quantitative response of corn roots to excessive soil water during their most sensitive growth stage, the vegetative stage, by using small lysimeters (81 x 65 x 32 cm). The specific objectives of this study are given below:

1. to determine the effect of temporary flooding on the development/growth of corn root during the vegetative stage of, by using fiber optics and photography techniques;
2. to quantify the nitrogen uptake and distribution of corn roots for four different excessive water stress levels using two different water table positions (surface flooding and with water table at 15 cm depth).

MATERIALS AND METHODS

Experiments were conducted in the environmentally controlled growth chambers located at the National Soil Tilth Laboratory and the Agronomy Department, Iowa State University, Ames, Iowa. Plastic containers, 81 x 65 x 32 cm each, were filled with soil from the Iowa State University Research Center at Ankeny, Iowa. This soil was not sieved, but was only cleaned of plant residue only, i.e roots and shoots. The soils at this experimental site are predominantly Nicollet loam soils in the Clarion-Nicollet-Webster soil association. Table 1 gives selected physical properties of Nicollet loam soil.

Table 1. Particle-size distribution, gravel percentage, and soil reaction of Nicollet loam soil (from Charkhabi, 1990)

Hor	Depth	Sand	Fi.silt	Co.silt	Clay	Gravel[a]	pH_w[b]
	cm	%	%	%	%	%	%
Ap	0-15	29.5	11.3	33.0	26.2	0.1	5.9
A1	15-25	28.7	13.1	32.1	26.1	0.4	6.1
A2	25-46	31.5	17.2	23.2	28.1	0.2	6.6
AB	46-56	34.4	10.8	27.4	27.4	1.1	7.0
Bw	56-76	38.6	9.2	24.9	27.3	2.2	7.1
BC	76-86	31.0	11.8	32.5	24.7	1.9	7.2
C1	86-102	40.1	10.8	26.8	22.3	3.0	7.7
C1	102-117	38.2	12.0	30.2	19.6	2.0	7.8
C1	117-135	39.2	11.8	29.1	19.9	2.2	8.0
C2	135-160	38.6	12.6	29.0	19.8	1.5	8.1

A transparent acrylic tube called a minirhizotron, 90 cm long and 40 mm in diameter, was positioned at a 27-degree angle from the container wall in nine of the lysimeters. Bottom ends of the tubes were sealed with a rubber stopper and sealant to keep water out. Black paint was sprayed on the top 20 cm of each tube to shut the light out. Tube openings were also closed with nontransparent plastic covers to keep out the light from the roots. Lysimeters with a minirhizotron were placed in the National Soil Tilth Laboratory (NSTL) growth chamber, and the other nine lysimeters were placed in the ISU Department of Agronomy growth chamber.

Experimental Treatments

The experiment was conducted in two parts. The first part of the study was designed to observe the qualitative response of roots in-situ by using fiber optics under four temporary durations of surface flooding for 3, 6, 9, and 12 days during the vegetative stage of corn. Each water table treatment was replicated twice. Treatments of surface flooding, in which water was maintained about 3 cm above the soil surface, were started at the 9th leaf stage of corn. This part of the experiment was conducted in the National Soil Tilth Laboratory (NSTL) growth chamber. The second part of experiment was designed to determine the quantitative response of the roots under surface flooding (for 3, 6, 9, and 12 days) and water table at 15 cm below the soil surface(6, 12, 18, and 24 days). These sets of treatments were also used to test the concept of SEW_{30} (currently known as " Sum of Excess Water " which relates yield reduction to the occurrence of a high water table) (Sieben, 1964) for root-dry matter. Sieben (1964) introduced the concept of SEW_{30} which quantifies the wet stress by summation of the days times water table in the 30 cm top of the soil. He calculated SEW_{30} as

$$SEW_{30} = \sum_{i=1}^{n} (30-WTD_i),$$

where WTD is the daily water table depth on day i, and n is the number of days. To compare the effect of flooding on root growth, an additional lysimeter was placed in each growth chamber where a subsurface drain was used to maintain the water table at 70 cm below the soil surface. The root growth in this lysimeter was treated as the control treatment (free from excess water stress). In the beginning of the experiment (before excess moisture treatments began) and after the excess moisture treatments were over, all lysimeters including the control lysimeters were surface irrigated when 50% of the available soil moisture was depleted by evapo-transpiration demand. This was done to avoid any stress due to moisture deficit.

Fiber-Optical Photography

The fiber-optic system used consisted of a light source, a flexible metal sheath containing glass viewing and light fibers (150 cm long), and an objective lens for focusing. In place of an objective lens, a camera was attached to a special adapter. The viewing end of the fiber scope was passed through a centered hole rubber stopper and fixed along with its metal sheath on a meter, marked wooden scale. The viewing end with rubber stopper or the eye-piece was in front of the wooden scale, as shown in Figure 1. The rubber stopper was used to fix the height of the viewing end and to make it flexible for rotation in the acrylic tube (minirhizotron). Peregrim (1982) mentioned a glare problem when the light source attached to the fiberscope was used as suggested by the manufacturer. Therefore, a separate simple light source was developed. This light source was made of a small searchlight reflector, a light bulb, and a back connection to an AC adapter. The bulb with searchlight was fixed on the wooden scale slightly ahead of the viewing end. Ektachrome EL 135 (400)[3] slide film was used in a Pentax camera for root photography. A 1/8 second exposure gave good results with one-push process development. Root photographs were taken at three soil depths (15, 30, and 45 cm) in the lysimeters for each of the water table and control treatments. The first set of photographs was taken a day before the flooding treatments began. Three sets were taken during the flooding treatments; one set was taken just before the end of each flooding treatment; and the last set of photographs was taken one week before harvesting (after 61 days of planting). Effort was made to take the photographs exactly at the same point at each depth, every time. To accomplish this, the degree of rotation from selected reference points was recorded during the first round of photography for each depth, which

[3]Reference to a trade or company name is for specific information only and does not imply approval or recommendation of the company or product by Iowa State University to the exclusion of others that may be suitable.

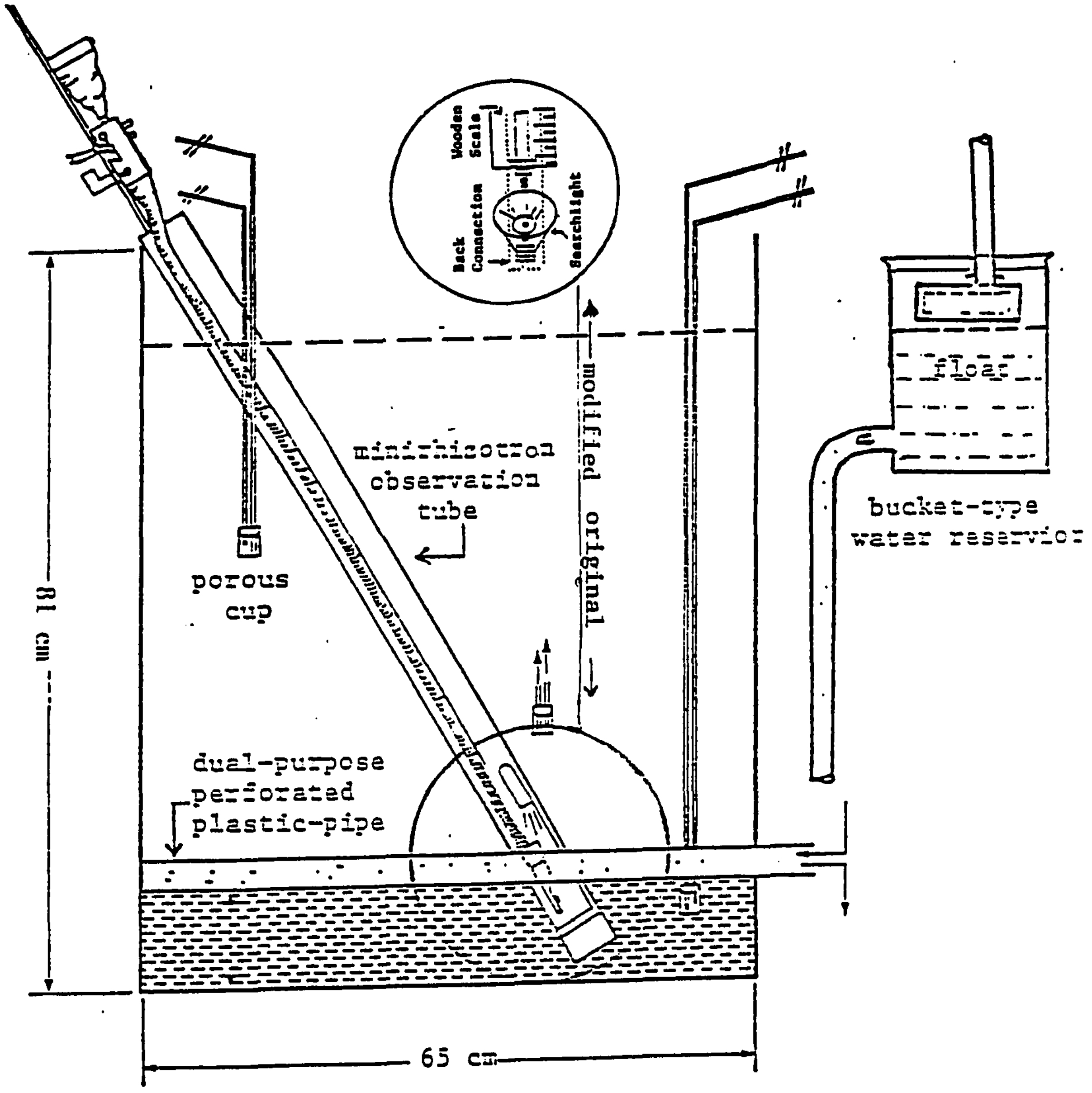

Figure 1. Schematic diagram of the lysimeter (with water table maintenance facility) placed in the growth chamber

was used as a guide to locate the same root and point for the next sets of photographs.

Root-Area Measurement

The developed negative films were projected on rigid screen by a table slide projector. The projected images were thirteen times the actual photographed area (9.04 cm^2) of the root. The projected images of the roots of each slide were traced on a transparent acetate sheet. Finally, these tracings were analyzed on AUTOCAD with a digitizing tablet for areal extent of roots (Figure 2).

Quantitative Measurement of Root

At the end of the experiment and after harvesting the corn plants, nine lysimeters located in the Agronomy growth chamber were brought to the Agricultural Engineering building for washing roots. Sufficient water was poured into the lysimeter to moisten the entire soil column the night before washing the roots. The next day, lysimeters were laid horizontally on a perforated wooden stand, and their plastic container was cut from the top and sides to expose the soil filled with roots. A gentle sprinkler was used to wash soil away from the roots. A metal screen also was kept on the soil column to reduce the water pressure further and avoid root loss. It took about 2 to 3 hours to wash all soil from each lysimeter; time was very much dependent upon root intensity in the soil.

After all roots were completely washed, the roots of all four plants in each lysimeter were separated from each other and measured for maximum and average length for each treatment. The roots were then air dried for 6 to 8 hours in the shade and then placed on the marked board to be cut into 15 cm lengths for determining the root distribution as a function of depth. Each part of the root was dried separately at 60°C. After being dried and weighed, roots of all four plants were ground for each 15 cm depth increment and analyzed for their nutrient (nitrogen) uptake.

RESULTS

Qualitative Measurements of Roots by Fiber Optics in the Minirhizotron

Table 2 shows the area of roots observed at three depths (15, 30, and 45 cm) under different surface flooding treatments. The first set of the roots was observed before the beginning of flooding treatment at the 9th leaf stage of corn and after 30 days of planting. Table 2 indicates that no root was found at 45 cm depth at this time. Comparison of the root area values obtained by the first set of photographs taken before the beginning of treatments showed significant differences at both depths (15 and 30 cm). The highest value of 1.75 cm^2 and the smallest value of 0.16 cm^2 were obtained at the 15 cm depth. Table 2 also shows the same kind of root-area differences for the 30 cm depth. Because the shoot measurements before the beginning flooding treatments were not significantly different (Ahmad et al., 1990), the differences in root-area values were unexpected. As flooding treatment increasingly suppressed root growth, the initial differences were dominant up to harvest. Because of these initial differences in the root area, the limitations of this technique made it difficult to compare directly the effects of flooding on root area.

Change in root area for each successive measurement was calculated to determine the flooding effect on the roots. Table 3 shows the average change in root area of two replicates of surface flooding treatment. Each value in Table 3 indicates a change in root area (cm^2) during the last three days, except for the last set (on the 54th day), which shows a change in root area during the last fourteen days before harvest. Table 3 shows positive as well as negative values. Positive values indicate an increase in the root area, whereas negative values indicate a decrease in the root area. Most of the negative values of root growth have been observed either at the time of raising the water for starting the flooding treatment or at the end of the flooding treatment. Table 3 also indicates negative root-area value for the control, which suggests that flooding alone has not been responsible for reduction in the root area. Even though the rate of growth of the root area was small, no negative change was observed under twelve days of flooding at the 15 cm depth; a zero root area change was observed at the 30 cm depth. Comparison of the developed negative photographs for the 15 cm with results of flooding treatments at others depths indicated that a relatively larger root (perhaps the corn crown-root) had been under observation, which showed lesser response to flooding. On the other hand, a zero value of root-area change at 30 cm indicated an impairment of root growth. A graphic relation was drawn between root-area change for the stressed and nonstressed plants for the fourteen days before harvest (Figure 3). Figure 3 shows that the maximum change in root area occurred at 45 cm and the minimum at 15 cm during the last period of vegetative growth for all flooding treatments. Figure 3 also indicates that root-area development was less under three days of flooding than at six and nine days of flooding. This result indicates root survival after six and nine days of flooding. The greater root-area change for six and nine days of flooding indicates that more new roots probably develop after the termination of flooding in comparison to the steady growth of roots after three days of flooding in the same growing period. Significant reduction of root area was recorded after 12 days of flooding in comparison with the other flooding treatments. This result indicates that the chance for survival of the roots may be much less after twelve days of flooding than after the other flooding periods (3, 6, and 9 days). Because individual observations under flooding in the same row of Table 3 had the same levels of stress, an average was taken to determine the average growth-rate which is given in the last column of Table 3. The average growth-rate indicated that growth-rate decreased with the duration of flooding. This reduction was less at 30 cm than at the other two depths (15 and 45 cm).

Quantitative Measurements of Roots

Table 4 presents the distribution of corn roots per plant (average of four plants) for each of the four stress levels (SEW_{30} = 90, 180, 270, and 360 cm-days) for both surface and water table at 15 cm below the soil surface treatments. This table shows that, in comparison with surface flooding, water table at 15 cm below the soil surface resulted in nearly twice as much in the root system in the first layer (15 cm) for the SEW_{30} values of 90 and 180 cm-days and about three times as much for the SEW_{30} of 270 and 360 cm-days. Table 4 also shows that the proportion of total root-system at all depths under water table at 15 cm below the soil surface was significantly greater than after surface flooding. The maximum length of root of 90 cm was observed under six days of water table at 15 cm below the soil surface (Table 5). The average root-length was greater under water table at 15 cm below the soil surface (72 cm) than surface flooding (60 cm). A graphical relationship was also drawn between the dry-matter weight (as a function of soil depth) and days of surface flooding (Figure 4).

Figure 4 shows that the root weight decreased with the duration of flooding at all depths. Figure 4 also compares the dry-matter weight for surface flooding treatments with that of the control treatment (no stress). Figure 5 shows a graphical relationship between the root dry-matter weight and days of water table at 15 cm below the soil surface. This figure shows that the root dry-matter weight, in comparison to surface flooding, increased with the duration of water table at 15 cm below the soil surface for the 0-15 cm depths. The root weight at the 15-30 cm depth was the greatest for the 24-days water table at 15 cm below the soil surface treatment, followed by 18, 6, and 12 days of water table at 15 cm below the soil surface.

Table 6 shows the average root dry-matter weight per plant as a function of SEW_{30} values for both flooding treatments. Table 6 shows that the root dry-matter decreased under both flooding levels, but this reduction was more pronounced with surface flooding than with water table at 15 cm below the soil surface. Dry matter weight was less than that of the control treatment at all levels of water table at 15 cm below the soil surface, but this reduction was not significant. This table also indicates an increase in root dry- matter weight with the longest periods of surface and water table at 15 cm below the soil surface.

A bar graph was developed to show the difference between the root dry-matter at the same values of SEW_{30} for two water table positions, and to evaluate the SEW_{30} concept for root yield (Figure 6). The hypothesis of dry-matter difference greater than zero was tested by a t-test. Analysis resulted in acceptance of the hypothesis and rejection of the alternative. This shows that the root dry-matter weights under water table at 15 cm below the soil surface were significantly greater than under surface flooding at all corresponding values of SEW_{30}.

Figure 7 shows that the difference between the root dry matter weight for the same value of SEW_{30} using two different water table levels (surface vs 15 cm below the soil surface). A regression equation ($DM_{\%gain} = 106.25 + 0.52\ SEW_{30}$; r^2=0.81) was developed to predict the percentage gain in root dry-matter from keeping water at 15 cm beneath the soil relative keeping it at the surface. This increase in the root-dry matter under water table at 15 cm below the soil surface signifies the effects of subirrigation and better oxygen exchange in the top 15 cm of the soil profile.

Nitrogen Uptake

Table 6 also shows the percentage of nitrogen in root and root uptake for four different values of SEW_{30} under both water table positions. Data in Table 6 indicate that the percentage of nitrogen in the root increased with the duration of flooding under both water table positions, except under 24 days of water table at 15 cm below the soil surface. The minimum concentration of nitrogen was found for the control treatment, followed by treatments of 6 and 24 days of surface flooding. The increase of nitrogen with flooding duration indicates an impairment of root function. Thus, in contrast to nitrogen concentration, nitrogen uptake decreased with the increase of surface flooding because of insufficient dry-matter at longer durations of flooding.

DISCUSSION

As explained, no effort was made to determine the quantitative response of roots by using fiber optics in the minirhizotron, and only the qualitative response under different durations of surface flooding was studied. The results presented in Tables 1 and 2 indicate that fiber-optics observation of roots via the minirhizotron method is not perfected yet. It was found that observations of roots near the tube before treatments gave were highly variable results. This was unexpected in light of the insignificant difference in shoot measurements. This result indicates that root contacts to tube (minirhizotron) were not more than a chance. For the minirhizotron results to have greater values, the roots observed at the soil-tube interface must have been representative of those present in the bulk soil. To improve this technique, the size, orientation, and the method of installation of the tubes and their relation to the reliability of results should be studied more thoroughly. The useful information obtained with the use of fiber optics in minirhizotron was that changes occur in roots with respect to the length of time surrounding the tube (Table 2). Observation of these changes (appearance and disappearance of roots) were useful in assessing the effects of treatments, and certainly is more helpful method than just measuring the presence of roots. The negative growth-value observed for control conditions raised the question of whether changes in root parameters observed at a particular spot along a tube wall were due only to treatments or to some other factors (i.e. movement of roots, location or the right spot, focusing of light on roots, or the tube itself as a rigid medium for growth). The answers to these questions are not definitive and call for more studies and replications within studies. This limitation could be overcome by increasing the area of the observation at a point, and also by increasing the number of observation points in each minirhizotron.

Root dry-matter weight, a quantitative measure of the quantity of photosynthate deposited in the roots, was obtained by washing the root of each lysimeter. Results given in Table 3 for the root distributions in the soil indicate that surface flooding had a more severe effect on both weight and length of root than did water table at 15 cm below the soil surface. On the average, the data obtained show that each surface flooding treatment caused a significant reduction in root dry matter. In contrast, the reduction in root dry matter, compared with that of the control, was not significant for water table at 15 cm below the soil surface. These results indicate that corn root has the capability of close to normal growth even if little oxygen is available to roots in the upper 15 cm of the soil profile.

It was observed that control lysimeter roots had many fine hairs, which increased the root area per unit area of soil. In fact, a small number of root hairs were observed under water table at 15 cm below the soil surface, and instead, white spongy roots were found throughout these lysimeters at deeper depths. Roots formed under surface flooding were dark brown, except for a few newly grown roots found at greater depths of the lysimeters. These results indicate that corn roots have the ability to grow in excessive soil-water conditions and that this ability increases when water is kept at 15 cm below the soil surface. The other difference found between the roots of the control and those treated with water table at 15 cm below the soil surface was the root diameter. Larger roots, especially in the first 15 cm zone, were found for water table at 15 cm below the soil surface, which might be the cause of the higher root dry-matter weights for water table at 15 cm below the soil surface.

SUMMARY

A growth-chamber experiment was conducted to determine the effect of two water table positions (3 cm above and 15 cm below the soil surface) and their different durations on the vegetative growth of corn. In the beginning of the experiment when no external plant matter was in the lysimeters' soil, qualitative changes of roots were observed for surface flooding, by the use of fiber optics. At the end of the experiment, nine of the lysimeters having endured different durations of surface flooding (3, 6, 9, and 12 days) as well as water table at 15 cm below the soil surface (6, 12, 18 and 24 days) treatments were cut and washed for quantitative measurement of roots. The roots images were traced on polyethylene sheet by using a slide projector; the tracings then were digitized on AUTOCAD to measure the root areas. Change in the root area over time was calculated for treatment effects. Root distribution at 15 cm intervals and the total root-weight also were determined for each treatment. This study resulted in the following conclusions.

1. Fiber optics with a minirhizotron could be used to determine the effect of treatments on the qualitative response of roots. The best advantage for using this technique was that it allowed the researcher to observe changes with time in-situ, something not possible with any other root-measurement technique. This technique however, lacked a direct comparative or representative measurement. Thus to obtain a representative sample, a larger root area should be examined and more research need to be

conducted to find a suitable method of installing the observation tube.

2. The quantitative root measurement showed that the maintenance of the water table at 15 cm resulted in a 160% increase in roots at a minimum level of stress (SEW_{30} of 90 cm-days), followed by 183, 291 and 275% increases in roots at 180, 270, and 360 cm-days of the same SEW_{30} values, respectively. This also suggests that more studies should be conducted to determine practical methods for improving yield in poorly drained areas using subirrigation methods.

Table 2. Root area (cm^2) observed at three depths (15, 30, and 45 cm) at three days interval under different duration of surface flooding.

Depth (cm)	DAP[a]	Root area in Cm^2 under various flooding levels 3DOF[b] Rep1	3DOF Rep2	6DOF Rep1	6DOF Rep2	9DOF Rep1	9DOF Rep2	12DOF Rep1	12DOF Rep2	Control
15	30	1.39	.00	0.16	1.81	1.75	.00	.00	1.65	2.30
	33	1.29	0.37	0.12	1.51	.00	3.12	.00	2.51	4.25
	36	2.31	0.81	0.21	3.62	2.55	5.20	2.52	2.23	5.31
	39	3.15	0.77	0.33	3.23	3.33	3.32	1.87	6.09	5.54
	42	2.80	0.71	0.40	3.43	3.43	1.51	2.72	5.67	5.03
	54	4.15	0.99	0.50	5.08	4.10	2.77	2.12	7.37	6.63
30	30	.00	3.21	.00	.00	1.20	0.91	0.90	.00	2.95
	33	1.34	2.68	0.40	0.65	0.97	0.42	0.66	0.95	5.32
	36	0.74	1.96	0.64	2.02	1.09	2.24	0.83	1.59	4.65
	39	2.75	1.31	1.54	2.51	2.44	3.88	1.59	2.00	4.84
	42	4.86	1.36	3.33	2.38	3.37	2.51	1.37	2.22	5.76
	54	6.92	2.88	5.26	2.93	3.89	5.26	1.80	2.63	7.86
45	30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	36	0.65	0.00	0.33	0.19	2.08	2.74	1.21	0.90	2.11
	39	2.02	1.07	0.38	1.69	2.28	2.99	2.06	1.19	2.71
	42	3.45	1.83	2.68	1.05	3.37	2.69	2.64	1.51	2.2
	54	3.70	5.42	4.63	4.12	7.48	3.33	4.10	2.00	8.82

[a]DAP = days after planting
[b]DOF = days of flooding

Table 3. Change in the root area (cm^2) as a function of different duration of surface flooding

Depth	DAP[b]	Cont.	3 DOF[c]	6 DOF	9 DOF	12 DOF	Av.[a] Growth Rate
15 cm	33	1.95	-0.10	-0.13	-	0.43	0.07
	36	1.06	0.73	1.10	1.44	0.62	1.05
	39	0.23	0.41	-0.14	-0.55	1.61	0.53
	42	0.51	-0.19	0.14	-0.86	0.21	0.21
	54	1.60	0.80	0.87	0.97	0.56	-
30 cm	33	2.37	0.41	0.53	-0.36	0.36	0.23
	36	-0.67	-0.66	0.81	0.97	0.40	0.73
	39	0.19	0.68	0.69	1.46	0.59	1.02
	42	0.92	1.08	0.83	-0.19	0.00	0.00
	54	2.10	1.79	1.24	1.64	0.42	-
45 cm	33	0.00	0.00	0.00	0.00	0.00	0.00
	36	0.00	0.00	0.00	0.00	0.00	0.00
	39	0.60	1.22	0.77	0.23	0.57	0.40
	42	-0.51	1.09	0.83	0.39	0.45	0.45
	54	6.62	1.92	2.51	2.38	0.97	-

[a]average of values in rows under the same levels of stress (cm^2/3 days).
[b]days after planting
[c]days of flooding
-no value (photograph was out of focus)

Table 4. Distribution of root dry matter of corn for different durations of surface and water table at 15 cm below the soil surface

Depth (cm)	control treatment	Average Dry Matter Weight of Roots, gms: Days of surface flooding 3	6	9	12	days of water table at 15 cm below the soil surface 6	12	18	24
0-15	9.65	5.86	4.15	4.05	4.35	8.93	9.05	11.59	12.33
15-30	1.81	1.20	0.50	0.26	0.44	3.72	2.08	3.07	5.10
30-45	5.99	0.46	0.10	0.04	0.15	4.06	1.95	1.49	1.65
45-60	2.23	0.23	0.24	0.00	0.10	2.34	0.77	0.60	0.00
60-75	0.39	0.11	0.00	0.00	0.05	0.39	0.30	0.25	0.00
75-90	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00

Table 5. Corn root length as a function of surface and water table at 15 cm below the soil surface

Stress level DOF[a]	SEW_{30} values (cm-days)	root length (cm) maximum	average
Surface flooding			
3	90	85.0	80.5
6	180	74.0	58.0
9	270	55.5	50.0
12	360	61.0	47.0
Water table at 15 cm below the soil surface			
6	90	90.0	83.5
12	180	85.0	78.0
18	270	80.5	67.0
24	360	60.0	50.5

[a]Days of flooding

Table 6 Effect of different SEW_{30} values on the average root dry matter weight, root nitrogen percentage, and nitrogen uptake per plant

Stress levels	SEW_{30} values (cm-days)	Root dry matter/plant (gm)	Percent of nitrogen in root/plant	Nitrogen root uptake/plant (mg)
Surface flooding				
	90	7.86	1.09	85.46
	180	4.99	1.17	58.38
	270	4.35	1.32	57.42
	360	5.09	1.35	68.72
Water table at 15 cm below the soil surface				
	90	19.6	0.90	176.40
	180	14.1	1.16	164.02
	270	16.9	1.02	173.29
	360	19.08	0.94	179.35
Control	opt.	20.06	0.90	180.54

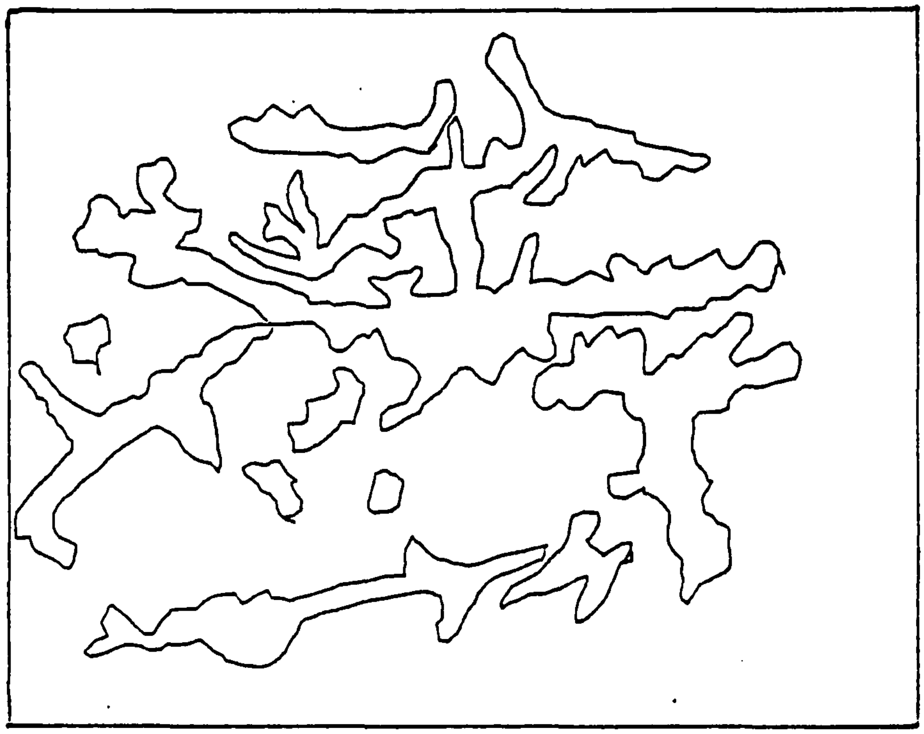

Figure 2. Projected image of roots on a transparent sheet

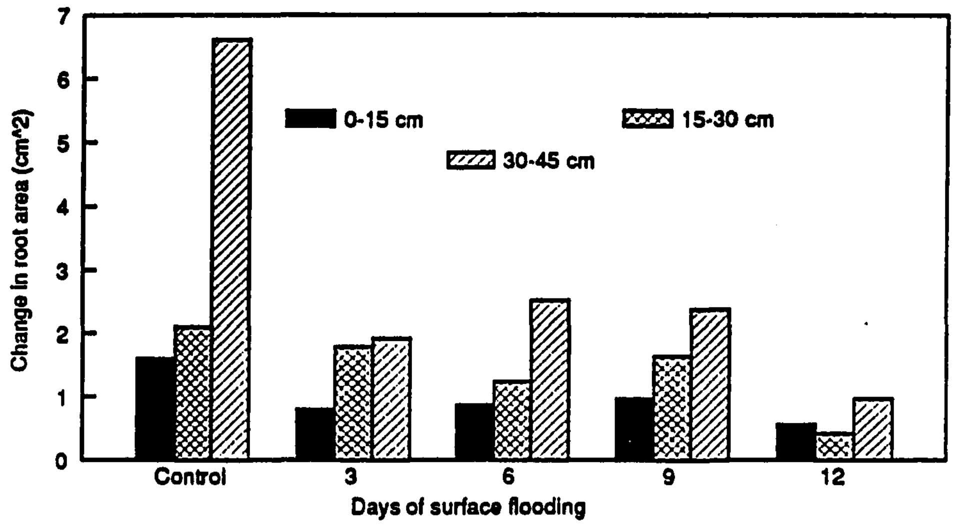

Figure 3. Root area change for stressed and nonstressed (control) plants before harvest

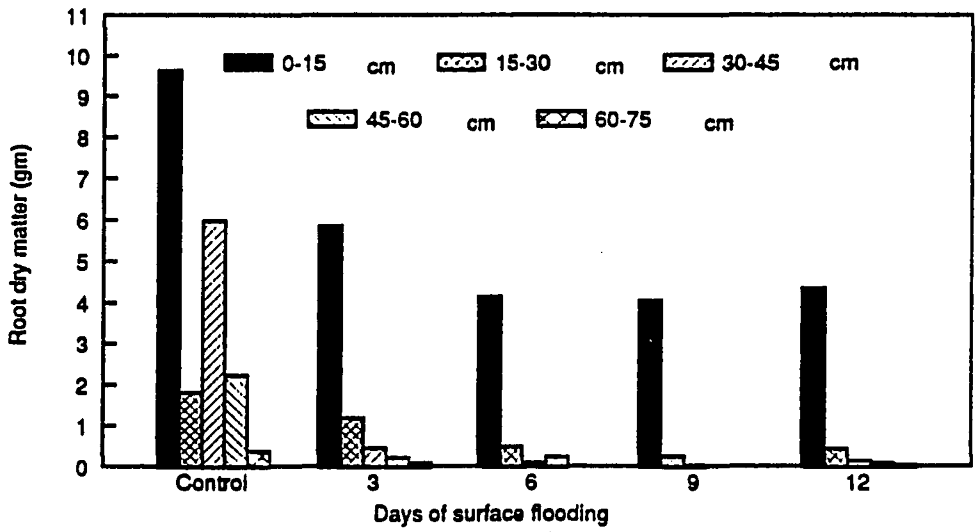

Figure 4. Root dry-matter weight as a function of soil depths under surface flooding treatment

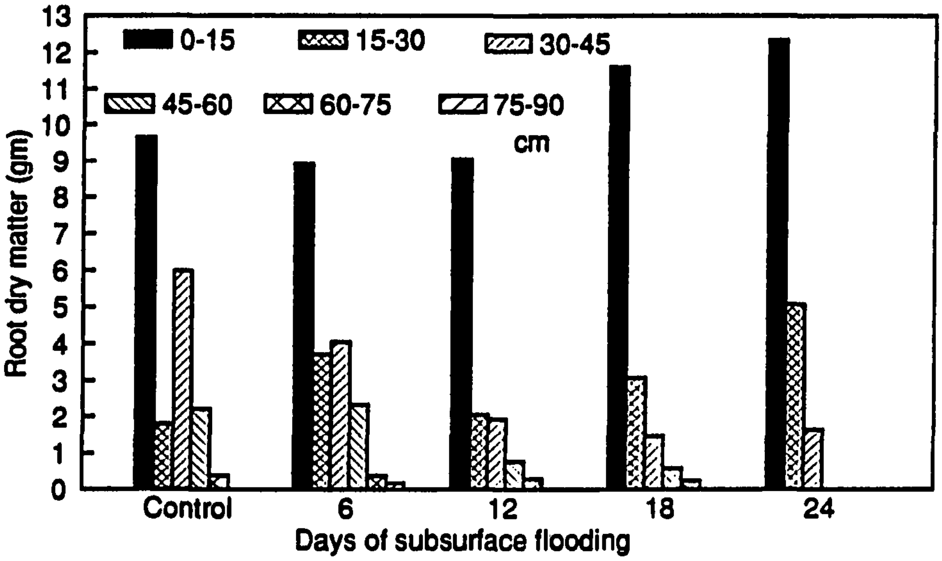

Figure 5. Root dry-matter weight as a function soil depths water table at 15 cm below the soil surface

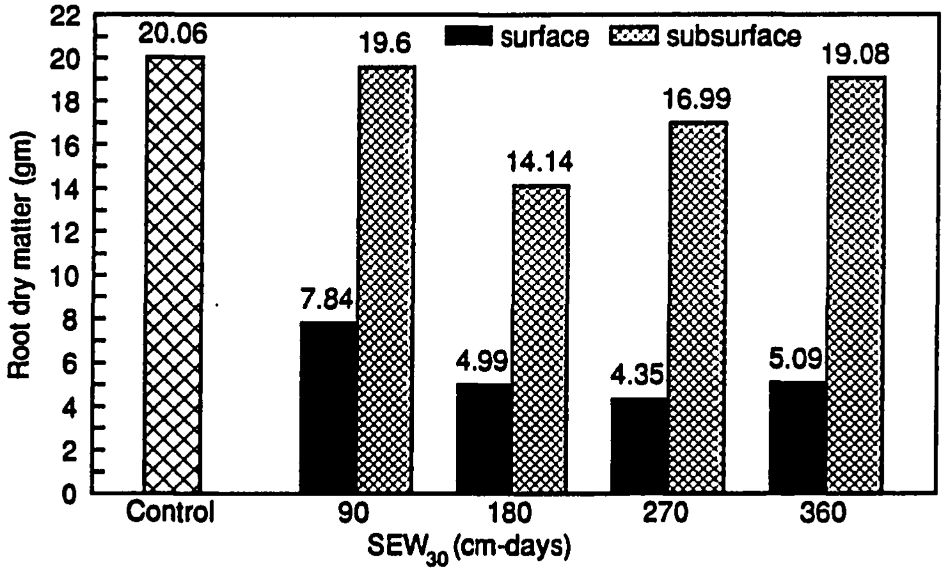

Figure 6. Root dry-matter weight as a function of SEW_{30} and water table positions

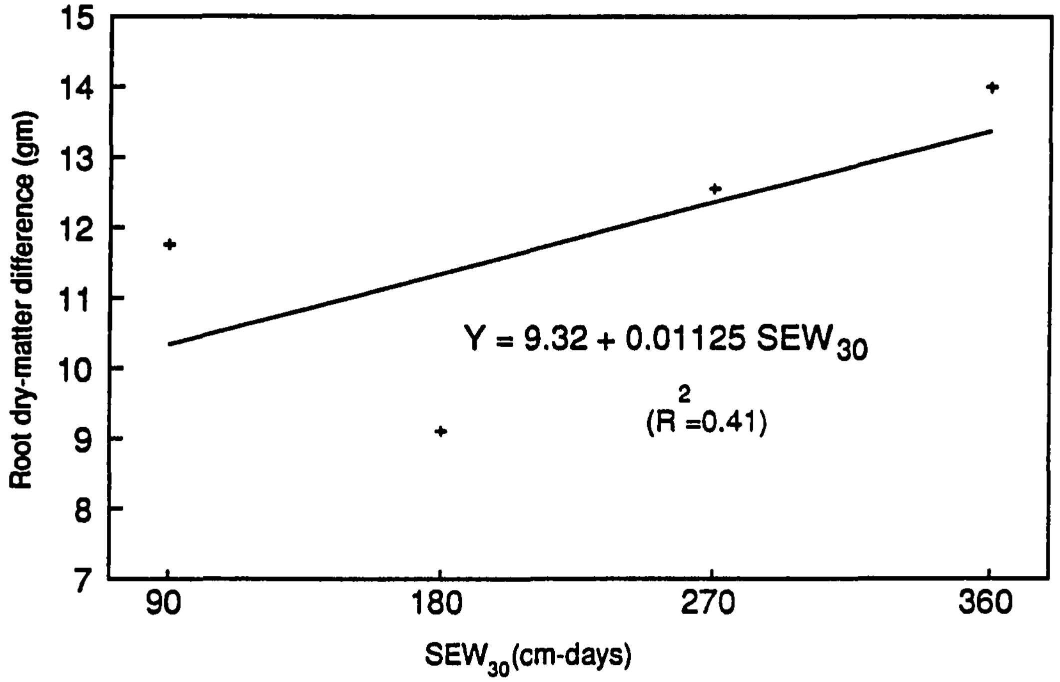

Figure 7. Linear regression equation to predict the percentage gain in root dry-matter under water table at 15 cm below the soil surface over the surface flooding treatment.

PART 3: EFFECT OF FOUR DIFFERENT STRESS LEVELS DUE TO EXCESSIVE WETNESS (SEW_{30}) ON CORN GROWTH IN FIELD LYSIMETERS

ABSTRACT

Experiments were conducted in field lysimeters to investigate the effects of different degrees of stress levels (due to excessive wetness) with SEW_{30} values equivalent to 90, 180, 270, and 360 cm-days on corn growth. Various plant growth parameters (plant dry matter, canopy height, and yield) were measured before, during, and after the stress periods. Two models were developed to predict corn yield as a function of SEW_{30} values and water-table position. The results of this study indicated that the concept of SEW_{30} can not be used satisfactorily to predict corn yields under waterlogged conditions.

INTRODUCTION

In designing agricultural drainage systems, it is important to know the drainage requirements of crops. Excessive soil-water conditions inhibit the exchange of air between soil and the atmosphere and thus result in oxygen deficiency. This deficiency subsequently inhibits both root respiration and total root volume, as well as water and nutrient transport by plant roots, and facilitates the formation of toxic compounds in soil and plants. The degree of crop susceptibility to damage by excessive soil-water conditions is dependent upon plant species, plant-development stage, soil and air temperatures, and duration of waterlogging. Considerable variation in excess-water tolerance exists between and within plant species (Gilbert and Chambelee, 1965) and the greater the duration of waterlogging, the greater is the damage (Leyshon and Sheared, 1974; Joshi and Dastane, 1966). This relation does not hold for all plant species, however (Heinrichs, 1970).

The timing, duration, and water-table level of excessive soil-water conditions during crop growth periods seem to have maximum impact on the final grain yield and the extent of injury to plants. Joshi and Dastane (1966) observed that flooding corn at the preflowering stage reduced yields significantly and that the longer the duration of flooding, the greater is the damage. Mukhtar et al. (1990) concluded that flooded corn was more susceptible to grain yield reduction at the early vegetative stage than at the late vegetative stage; Evans and Skaggs (1984) observed that flooded corn was more susceptible to grain yield reduction at the late vegetative stage. Most other studies concluded that the greatest crop damage and the maximum yield-reduction occurred during the early vegetative stage (Leyshon and Sheared, 1974; Kanwar et al., 1988; Fausey et al., 1985; Bhan, 1977; Chaudhary et al., 1975; Cannell et al. 1980; Zolezzi et al., 1978; Howell and Hiler, 1974; Ritter and Beer, 1969; Singh and Ghildyal, 1980).

To improve the root environment of plants for optimal yield, some studies have attempted to describe the relation between crop yield and excessive soil-water conditions. Sieben (1964) introduced the concept of the sum of the exceedence values of the water level known as the "sum of excess water" (SEW_{30}), which relates yield reduction to a high water-table during the growing season. Hiler and Clark (1971) proposed methods of characterizing crop susceptibility (CS) values in controlled situations and in the field. Ravelo et al. (1982) and Hardjoamidjojo et al. (1982) used the stress-day index (SDI) model, introduced by Hiler (1969), to measure the degree of stress caused to plants under excessive soil-water conditions. Williamson and Kriz (1970) used lysimeters to determine that most crops gave maximum yield when the water table was 30 cm below the surface.

The design of drainage and of subirrigation systems requires knowledge of the crop stages sensitive to excessive soil-moisture conditions. An optimal level of moisture stress for a crop may be the one causing a nonsignificant yield response to wetness under given climatic and agronomic conditions. Determining the optimal stress level first requires a study of the crop's sensitive growth stages that focuses on the range of stress levels, from the least to the critical. Additionally, it is important to obtain quantitative evidence of the adverse effects of high water tables in terms of growth rate and yield. Very few studies have been conducted where the effects of water table position on crop growth have been quantified. Therefore, the overall objective of this study was to investigate the response of corn to two water table positions during the vegetative stage, one of the plant's most sensitive stages to excess water. The specific objectives of this study were:

1. to determine under field conditions the effect of four different stress levels (SEW_{30}) and two water table positions (one at the surface and second at 15 cm below the surface) on corn growth and yield during the vegetative stage
2. to determine an optimal stress level due to excessive wetness (SEW_{30}) for corn under temporarily controlled flooding in field lysimeters.

MATERIALS AND METHODS

Experiment Site

The experiment site for this study was located at the Iowa State University Research Center in Ankeny, Iowa. The soils at this site are predominantly Nicollet loam soils in the Clarion-Nicollet-Webster Soil Association. Nicollet soils are characterized as naturally somewhat poorly drained soils. Some of the physical properties of these soils are given in Table 1. An area of 15 m x 48 m was selected for this experiment near the Agronomy and Horticulture experimental areas of the subirrigation project. This area was about 150 m east of the overhead water reservoir supplying irrigation water to experimental crops and was about 200 m west of the water pond storing subsurface drainage water drained from the entire experimental area. The surface slope of the site area was about 1.5 percent, towards the water pond.

Table 1. Particle-size distribution, gravel percentage, and soil reaction of Nicollet loam soil (from Charkhabi, 1990)

Hor	Depth cm	Sand %	Fi.silt %	Co.silt %	Clay %	Gravel[a] %	pH_w[b] %
Ap	0-15	29.5	11.3	33.0	26.2	0.1	5.9
A1	15-25	28.7	13.1	32.1	26.1	0.4	6.1
A2	25-46	31.5	17.2	23.2	28.1	0.2	6.6
AB	46-56	34.4	10.8	27.4	27.4	1.1	7.0
Bw	56-76	38.6	9.2	24.9	27.3	2.2	7.1
BC	76-86	31.0	11.8	32.5	24.7	1.9	7.2
C1	86-102	40.1	10.8	26.8	22.3	3.0	7.7
C1	102-117	38.2	12.0	30.2	19.6	2.0	7.8
C1	117-135	39.2	11.8	29.1	19.9	2.2	8.0
C2	135-160	38.6	12.6	29.0	19.8	1.5	8.1

With 2 m between two rows, the site area was divided into 24 subplots for 12 lysimeters in each row. Twenty-four box-type lysimeters were constructed, but 18 were installed in the center of the 18 subplots, as required by this experiment. Figure 1 shows the topographic map of the site and the layout of the lysimeters.

Construction of the Lysimeters

Five 6.2 mm-thick plastic sheets (four for each of the four sides of a rectangular box and one for the bottom) were placed together and bolted by using aluminum angle irons to create each of the 24 box type lysimeters.

Each lysimeter was 229 cm long, 90 cm wide, and 152 cm deep (Figure 2). The corners of the lysimeters were treated with silicone building and glazing sealant to make them waterproof. Ten cenimeters from the bottom of the lysimeter, a 7.6-cm hole was made on one side of the lysimeter with a power saw. An aluminum pipe of same size as that of the hole, which was welded across an aluminum plate, was passed through this hole. To make this hole watertight, the aluminum plate was glazed with silicone and bolted on the outside of the lysimeter hole. To raise or lower water in the lysimeter, a 10 cm diameter and 220-cm long plastic tile drain with a cap at the end was clamped to the aluminum pipe. The outside of the aluminum pipe was coupled with a 5 cm diameter PVC pipe connecting the water sump to the lysimeter (Figure 2). The water sump was a 183 cm long PVC pipe 38 cm in diameter. A PVC cap closed this sump pipe at the bottom with plastic cement. An adjustable float system

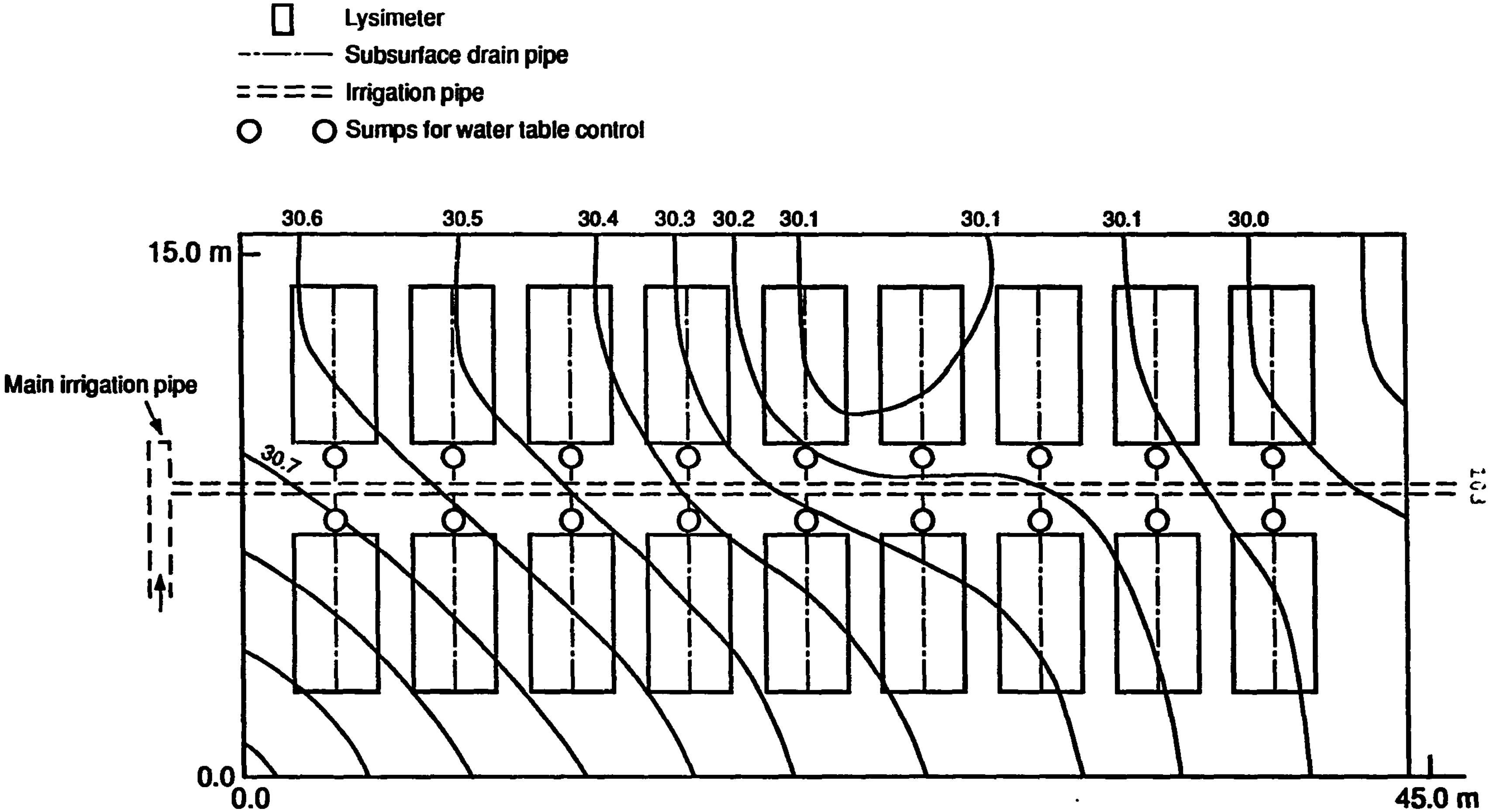

Figure 1. Location and layout of field lysimeters at the Ankeny Research Center. Figure also shows the contour lines

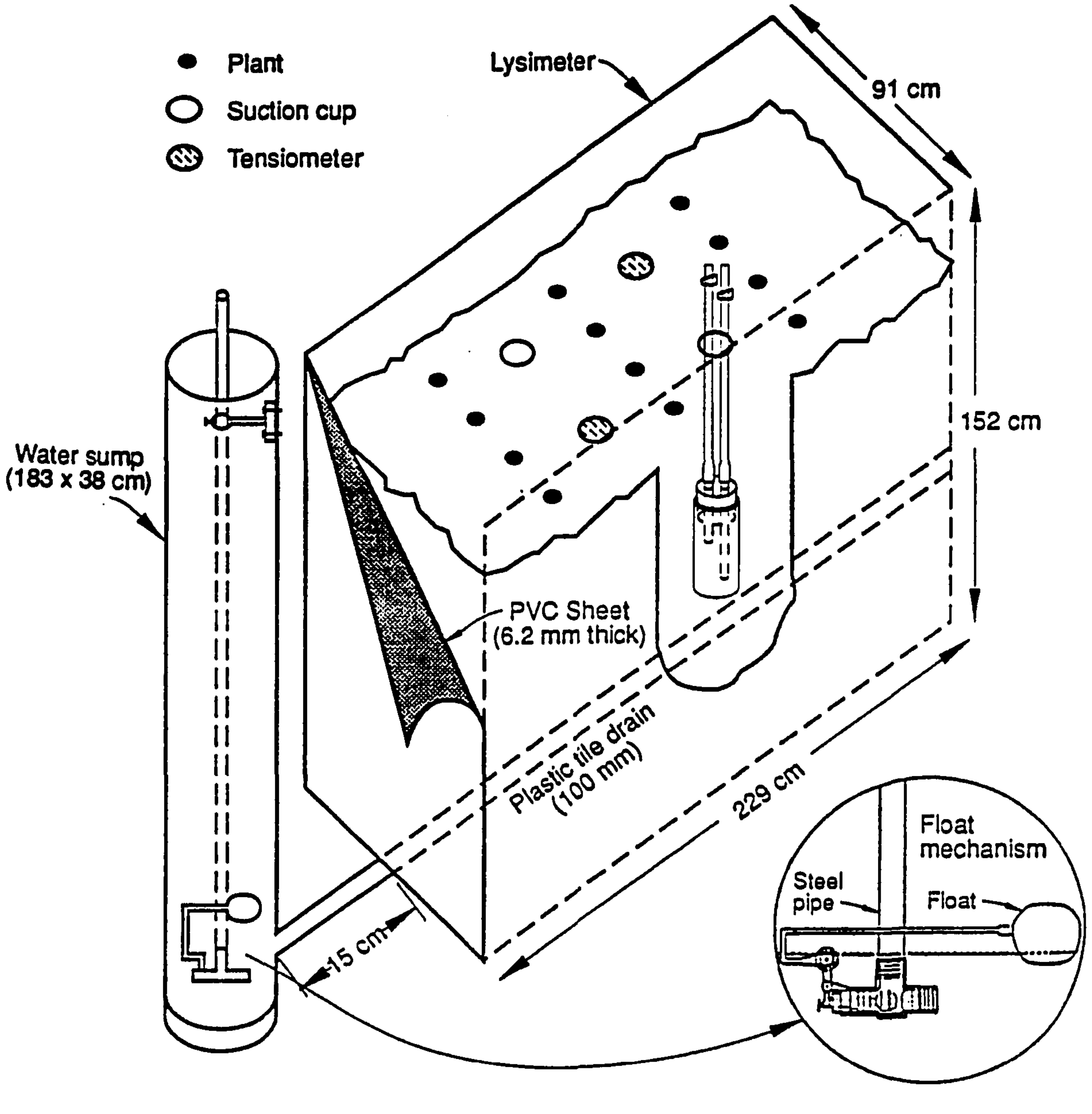

Figure 2. Schematic sketch of a field lysimeter with float type mechanism to maintain water table

was installed in the water sump to control the water table level. The float system consisted of a float and a steel pipe (Figure 2). The steel pipe was movable in an iron ring that was fixed at the top inner side of the sump pipe and had an adjustable bolt-lock fixing the height of float system to obtain the required water table height in the lysimeter.

Lysimeter Installation

After all lysimeters had been constructed, they were moved to the installation site in a pickup truck. Soil profile was excavated in 30-cm layers to a depth of about 150 cm by using a grave-digging machine (Figure 3). Each layer of soil was separated by a plastic sheet and a wooden board. Once the excavation was completed for placing the lysimeter box and the sump in the pit, a lysimeter box (without water sump) was placed in the excavated area, and each soil layer was repacked and compacted inside the lysimeter to match the original vertical soil profile and bulk density. After each layer was placed in the lysimeter, it was ascertained that soils were well leveled and compacted. Surplus surface soil, if any, was saved for future use. At the end of the lysimeter box installation, the water sump was connected to the lysimeter and to the plastic tile drain. The first bottom foot of area around the sump was filled with fine concrete, and the rest of the area up to soil surface was filled with excavated soil. The same procedure was repeated for the installation of all other lysimeters. Soil in almost all lysimeters settled during experimental treatments (flooding). The

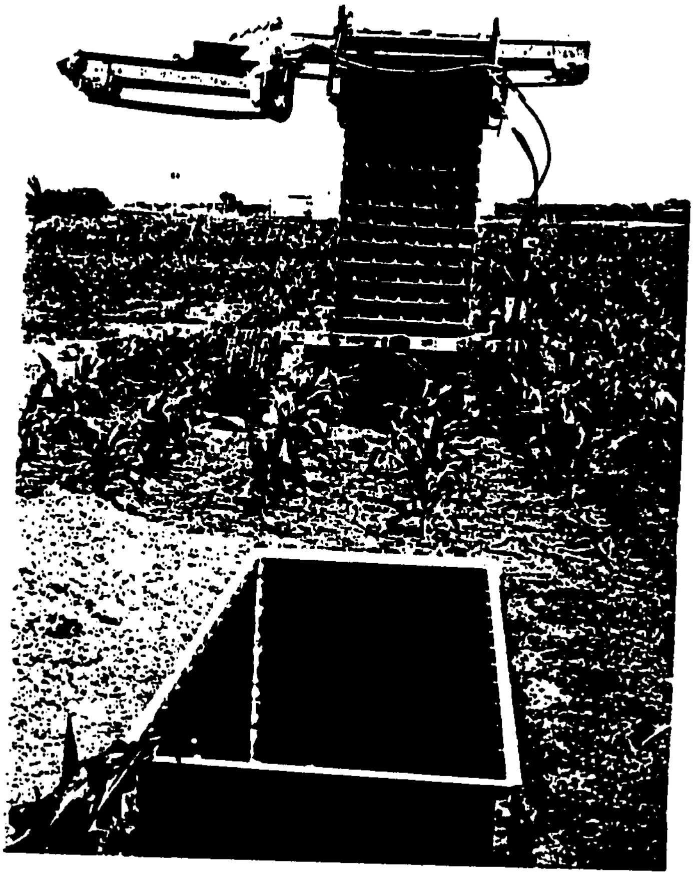

Figure 3. Grave-digging machine used for excavation. Figure also shows lysimeter embedded in the excavated pit

lysimeters were then refilled with surplus soil saved earlier to bring the soil depth in the lysimeters to the original depth.

Difficulties During Installation

The main difficulty during installation was the presence of high water tables for some of the lysimeters. Dewatering the excavated pits and cleaning the mud from the digging machine decreased the working efficiency of the machine and delayed the installation of lysimeters. Efficiency decreased even more after a rainfall and once when the digging machine sank into a pit. The other difficulty arose when the machine cut a tile drain at the bottom of two pits, which required the removal of much of the mud and water before the lysimeter could be installed in those pits.

Instrumentation of the Lysimeters

Instrumentation was provided according to the requisites of data collection (Figure 2). To determine the actual position of the water table in the lysimeter, a plastic tube-well (2.54 cm in diameter and 150 cm long) was installed in the center of the lysimeter. A set of solute suction cups was provided to take soil-water samples from each of the lysimeters, at depths of 60 and 90 cm. To determine the proper time of irrigation, a neutron probe was installed in each of the lysimeters. To measure moisture tension, two tensiometers, each with two 2-mm-thick PVC tubing and a 100 kpa porous cup (7 cm long and 2 cm in diameter) were installed in each lysimeter at depths of 30 and 60 cm.

Planting

This experiment was conducted in 1989 and 1990. Because construction and installation of lysimeters delayed direct planting in the first year, corn seeds were planted in 15-cm diameter and 25-cm-tall plastic pots on May 28, 1989. Four seeds were planted in each pot, and the number of plants per pot was thinned to two after germination. These remaining two plants were transplanted to the lysmeters and were finally thinned to a single plant after a week. Three rows were planted in each lysimeter. Four plants were kept in each row, with 10 cm from the sides of the lysimeter and 20 cm between plants, which gave a total of 12 plants in each lysimeter (Figure 2). The first transplanting of corn was performed on June 18 in 13 of the lysimeters, 21 days after planting. The second transplantation was performed on July 1 in the other five lysimeters, 31 days after planting. Transplanting was accomplished by digging pot-size grooves in the lysimeter and then by putting the pots in the grooves after removing the pot box. Efforts were made to prevent roots from being exposed to light. Plants were irrigated immediately after transplanting.

In 1990, seeds were directly planted in lysimeters on May 10. Thirty-six corn seeds were planted in each lysimeter and then thinned to 18 plants per lysimeter. Three plants were harvested before flooding treatments were begun, and three plants were harvested after 24 days of floodings, when all treatments were over. Twelve plants were kept in each lysimeter until final harvest for grain yield analysis. In both years, fertilizer application rate of 200 kg N (urea), 60 kg P (P_2O_5), and 60 kg K (K_2O) per hectare were applied before sowing.

Water Table Treatments

This experiment consisted of nine treatments each replicated twice. Eight of the treatments maintained the water table at two different positions (either at the surface or 15 cm below the surface) each with four different durations. The ninth treatment was the control treatment where the water table was maintained at 90 cm. The same level of stress due to water table (Sieben's SEW_{30} concept) was applied by maintaining the water at two different water-table positions (0 and 15 cm below the soil surface) for different numbers of days. Sieben (1964) introduced the concept of SEW_{30} which quantifies the wet stress by summation of the days times water table in the 30 cm top of the soil. He calculated SEW_{30} as

$$SEW_{30} = \sum_{i=1}^{n} (30 - WTD_i),$$

where WTD is the daily water table depth on day i, and n is the number of days. Water was raised and maintained in the lysimeters by adjusting the float system in the water sump to a required position. To confirm the required water table position, daily water table depths were observed by using the observation well installed in the center of each of the lysimeters. At the end of the flooding treatment or after any major rain event, water was pumped from the sump by using the sump pump. Table 2

Table 2. Discription of water table treatments

Duration of stress due to excessive wetness (days)	Depth of water table beneath the soil surface(cm)	Stress levels in SEW_{30} values (cm-days)	Total stress level in SEW_{30} values (cm-days)
Surface flooding treatments			
3	0	30	90
6	0	30	180
9	0	30	270
12	0	30	360
Water table at 15 cm below the soil surface			
6	15	15	90
12	15	15	180
18	15	15	270
24	15	15	360

presents the details of these treatments. Because the experimental design was a randomized complete block, all nine treatments were applied to each row (block) of lysimeters and repeated.

Irrigation of Lysimeters

Before and after the flooding treatment, the water table was maintained at 90 cm in the lysimeters by using the subsurface tile drain and a float system. A separate pipeline was installed and connected to the main irrigation line coming from the overhead water tank. A water meter was connected between the pipeline and the sump of each lysimeter to record the amount of water used by individual lysimeters (data not presented). Surface irrigation was applied when the soil water tension was 0.045 Mpa. No surface irrigation was applied to lysimeters with flooding treatments. Only control lysimeters were irrigated. Selected data on the weather conditions (from a weather station near by the site) during the two seasons are presented in Table 3.

Table 3. Weather conditions during 1989 and 1990 Corn Season

Month	Temperature Max. (°C)	Min.	Rainfall total (cm)	Seasonal total rainfall (cm)
1989				
May	22.88	9.50	10.24	
June	26.16	14.61	9.32	
July	29.83	18.55	11.15	41.45
August	28.26	16.55	10.74	
Sept.	22.77	8.11	0.00	
1990				
May	19.27	8.00	11.96	
June	26.38	16.16	25.22	
July	27.27	17.61	22.84	68.07
August	27.38	17.00	5.89	
Sept.	25.83	12.77	2.16	

DATA COLLECTION

Plant Measurements

Plant-growth parameters such as canopy height, shoot dry matter, and final grain yield were measured. Excessive-water treatments were begun at the sixth-leaf stage. On the day before treatments began, the heights of all plants in the lysimeters were measured. Canopy height was measured as the distance from the ground surface to the top flag leaf. Each of the 12 plants in the lysimeters was assigned a number to facilitate the collection and recording of individual plant data. At harvest, ears were removed from the plants, and plants were cut within lysimeters and put in separate jute bags. On the same day, ears collected from each lysimeter were shelled and passed through a moisture meter in the Grain Laboratory at Iowa State University to determine the moisture content of the grain. Plants were oven-dried at 60°C for shoot dry matter at the Iowa State University Agronomy Farm, 12 kilometers west of Ames. The same procedure was followed in both years, except that some additional measurements were made in 1990. The additional measurements included harvesting of three plants in each lysimeter before water table treatments were begun and harvesting of three plants when all water table treatments were over.

Data on canopy height, shoot dry weight, and grain yield were statistically analyzed with the PROC GLM in SAS and the Least Significant Difference (LSD). For comparisons among stress levels at two water-table positions, the data on control treatments were not included because these data represented a zero level of stress.

RESULTS

Grain Yield

In the two growing seasons, four different levels of water stress at surface flooding and water table at 15 cm below the soil surface were applied to corn (Pioneer 3751) during its vegetative stage in the field-type lysimeters. All treatments were repeated in both years. The yield data of five lysimeters in 1989 (in which transplanting was done on July 1) are not included because yields of these lysimeters were very low. These low yields might have been due to the transplantation of large plants. The high temperature on those days (during and after transplanting) and at the beginning of experimental treatments (flooding) after six days of transplanting in these lysimeters might also be the causes of low yields. Thus, for statistical analysis, 1989 data were treated as a single replication (taking the average of two data points if both replications were transplanted on June 18), and 1990 data as two replications.

Grain yield of corn for both water-table positions (surface flooding and 15 cm below the soil surface) was affected by the flood duration of each stress level (equivalent to SEW_{30} values of 90, 180, 270, and 360 cm-days). The analysis of variance (Table 4) shows that the effects of two water-table positions and stress levels (SEW_{30} = 90, 180, 270, and 360 cm-days) for each water-table position were highly significant for grain yield. The analysis of variance also shows that the variation in grain yields in both years were nonsignificant. Control and the low-stress level (SEW_{30} = 90 cm-days) treatment showed greater yields in 1989 than in 1990, which was not true for treatments with higher stress levels (SEW_{30} = 180, 270, and 360 cm-days), especially for surface flooding. These findings might reflect the effect of larger rainfall amounts in 1990 than in 1989. A graphical relation between SEW_{30} values and average grain yields per plant is shown in Figure 4, which shows, above the bar, average grain yield as a function of SEW_{30} values for both water table positions. Figure 4 illustrates that the effect of surface flooding was much more severe than that of water table at 15 cm below the soil surface. Figure 4 also indicates that grain yield for the control treatment was significantly greater than for the other treatments. The least significant values are also given in Figure 4. These values indicate that stress due to surface flooding reduced yield far more than did stress due to water table at 15 cm below the soil surface. When the water table was maintained at surface flooding, grain yield decreased significantly among 3 days (SEW_{30} = 90 cm-days), 6 days (180 cm-days), and 12 days (360 cm-days) of flooding treatments, but not between 6 days (180 cm-days) and 9 days (270 cm days) of flooding treatments. When the water table was maintained at 15 cm below the surface, grain yield decreased as the duration of flooding increased between 6 days (90 cm-days) to 18 days (270 cm-days) of flooding although differences were not statistically significant. The grain yield increased when stress level was increased from 18 days to 24 days (360 cm-days) of water table at 15 cm below the soil surface. A comparison among grain yield means shows that three days of surface flooding and 6, 12, and 24 days when the water table was maintained at 15 cm below the surface did not produce significant differences in grain yields. This comparison also shows that 6 days of surface flooding, and 18 and 24 days of water table at 15 cm below the soil surface did not produce significant differences in grain yields.

Percentage of grain-yield reductions obtained from each of the eight flooding treatments in comparison with the control treatment were calculated. Significant differences in percentage yield reductions were found at two water table positions. Figure 5 shows graphically the average yield reduction at various SEW_{30} values for two water table positions. This figure indicates that as flood duration increased, so did yield reduction. Similar results were obtained by many other researchers studying surface flooding effects on grain yield (Bhan, 1977; Joshi and Dastane, 1966; Chaudhary et al., 1975; Oosterhuis et al., 1990; Mason et al., 1987). The maximum percentage grain-yield reduction for surface flooding (55.74%) occurred for 12 days of flooding (SEW_{30} = 360 cm-days) and was greater than the percentage yield reduction (34.65%) for 18 days of water table at 15 cm below the soil surface. The range in percentage yield reduction (55.74 - 27.07 = 48.17%) was also greater for surface flooding than for water table at 15 cm below the soil surface (34.65 - 21.38 = 13.27%).

Linear regression models between grain yield per plant and SEW_{30} values for both water-table positions were developed. These models show that at both water-table positions, the average grain yield of corn decreased linearly with increased SEW_{30} values. Linear regression equations and models for grain yield production as a function of both SEW_{30} values and water table positions are presented in Figure 6. The high R^2 (0.99) value for the model of surface flooding shows that the relation between grain yield and SEW_{30} could explain more than 99% of the variability. The model for water table at 15 cm below the soil surface gave lower R^2 (0.68) value. The reason for this lower R^2 value was a decrease in grain yield between 6 and 18 days of water table at 15 cm below the soil surface as well as an increase in grain yield for the 24 days of water table at 15 cm below the soil surface giving a larger variability.

Shoot Dry Matter

The first response of the corn plant to wet stress was reduced shoot growth. Shoot growth was reduced for all levels of the applied stress and was more visible for stress due to surface flooding than for stress due to water table at 15 cm below the soil surface. In both years, shoot dry matter was obtained at the final harvest, after the removal of ears. But in 1990, two additional harvests were made (one before water table treatment at the sixth-leaf stage and one after the water table treatment on 60th day after planting) to obtain the growth rate of corn during the vegetative stage. Shoot dry matter evidenced responses to wet-stress levels (at both water table positions) similar to those evidenced by grain yield.

Overall shoot dry matter decreased with increased stress at both water table positions. This decrease was greater at surface flooding than at water table at 15 cm below the soil surface. The analysis of variance (Table 4) for shoot dry matter shows a significant difference at the 0.05 level for both years, which was not true of grain yield. This difference might be due to a hailstorm in late August 1989, which did not affect grain yield because the crop had almost matured but that cut off the leaves and tops of plants and reduced shoot dry matter. Table 4 shows that shoot dry matter was highly significant at two water table positions and for all four SEW_{30} values (90, 180, 270, and 360 cm-days) at both water table positions. Figure 7 graphically shows relation between shoot dry matter yield per plant and SEW_{30} values, as well as the mean shoot dry matter values, above the bars. This figure also illustrates clearly the differences between shoot dry matter at two water table positions and the reduction of dry matter with increase of SEW_{30} values for both water table positions. Comparisons of shoot dry matter means (Table 6) by $LSD_{0.05}$ indicates that shoot dry matter decreased significantly among 3, 6, and 12 days of flooding (with SEW_{30} values equal to 90, 180 and 360 cm-day), but not between 6 and 18 days of water table at 15 cm below the soil surface (90 and 270 cm-days of SEW_{30}). The mean shoot dry matter values for water table at 15 cm below the soil surface (Table 6) shows no significant difference among the four stress levels.

The percentage decrease in shoot dry matter in comparison with the control treatment was also calculated. The relationship between average percent shoot dry matter reduction and SEW_{30} values for both water table positions are shown in Figure 8, illustrating that dry matter reduction increased with the duration of flooding at both water table positions. The exception was an increase in dry matter between 18 and 24 days of water table at 15 cm below the soil surface. The range in percentage reduction was greater for surface flooding (50.01 - 23.31 = 29.70%) than for water table at 15 cm below the soil surface (24.70-17.38 = 7.32%). The difference between shoot dry matter reduction for the same SEW_{30} value at two water table positions (surface vs. water table at 15 cm below the soil surface) also increased with stress levels, but the difference (5.93%) at minimum stress (SEW_{30} = 90 cm-days) imposed under both water table positions was not significant.

The percentages of shoot growth reduction (PGR)[4] due to treatments in relation to the control treatment were calculated for the 1990 data from the first two harvests, after 36 and 60 days, respectively. The relation between the PGR and SEW_{30} values for two water table positions (Figure 9) indicates that shoot reduction in relation to control was greater at surface flooding than when water table was maintained at 15 cm below the surface. Percentage growth reduction increased with the duration of flooding at both water table positions but was less for 24 days of water table at 15 cm below the soil surface (SEW_{30} = 360 cm-days) than for 18

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[2]PGR = {1 = [Growth (treatments)/Growth (Control)]} x 100
Growth = {shoot dry weight (after treatment - before treatment)}

days of water table at 15 cm below the soil surface (270 cm-days). The PGR difference (26.90%) for the same minimum stress value (SEW_{30} = 90 cm-days) was significant and increased with stress except for the 270 cm-days of the SEW_{30} value.

Regression models were developed between dry matter at final harvest and SEW_{30} values and plotted with the observed mean values of dry matter (Figure 10), showing that dry matter decreased linearly with the SEW_{30} values for surface flooding, which was not true of water table at 15 cm below the soil surface. Because dry matter decreased from 6 to 18 days of water table at 15 cm below the soil surface and increased from 18 to 24 days of water table at 15 cm below the soil surface, the best model to predict dry matter for water table at 15 cm below the soil surface was at the 2-degree polynomial (Figure 10).

Canopy Height

The analysis of variance in Table 4 shows significant differences for canopy heights at harvest for both water table positions and SEW_{30} values. Canopy height was greater for treatments of water table at 15 cm below the soil surface than for treatments of surface flooding. The treatment means (canopy height) compared by $LSD_{0.05}$ showed nonsignificant effects of water table at 15 cm below the soil surface and significant effects of surface flooding. The comparison also showed that there was no significant difference between canopy heights obtained at the minimum stress level (SEW_{30} = 90 cm-days) imposed on the two water table positions. To compare the effects of SEW_{30} values at each water level, a graphical relationship was developed between the SEW_{30} values and the canopy height at harvest (Figure 11), showing the canopy height values for control treatment and illustrating that, with surface flooding, although not with water table at 15 cm below the soil surface, canopy height decreased sharply when stress levels increased.

Figures 11 and 12 illustrate the graphical relations between days-after-planting and canopy height responses to different levels of stress for two water table positions and for the control. These figures show that both water table positions reduced canopy height more than the control treatment, but this effect was more distinct for surface flooding. The figures also illustrate a greater spread in canopy heights for all four levels of surface flooding than for water table at 15 cm below the soil surface.

The maximum canopy height (211.87-cm) was for the control treatment followed by 12 days of water table at 15 cm below the soil surface (SEW_{30} = 180 cm-days). The minimum canopy height (138.79-cm) was for 12 days of surface flooding (SEW_{30} = 360 cm-days).

DISCUSSION

Corn yields varied in response to both water table positions (surface and 15 cm below the soil surface) and to durations of flooding at each water table position. This variation was greater for surface flooding than for water table at 15 cm below the soil surface among SEW_{30} values at each depth. The yield response at the lowest stress level (SEW_{30} = 90) was nonsignificant under both water table positions. Similar results were obtained for shoot dry matter and canopy height.

To predict grain yield accurately for higher stress values, the SEW_{30} concept needs to be improved either through the development of coefficients or a separate equation for every water table depth from 0 to 30 cm as well as for all other possible combinations. It is impossible to determine coefficients or prediction equations for all conditions; consequently, the concept might best be improved by minimizing prediction error--as was attempted in this study--by dividing the wet stress zone (30 cm) into two subzones and by developing crop response (for grain yield, and other growth parameters) vs. SEW_{30} values for each subzone.

Visual observation indicated marked differences in growth parameters (shoot dry matter and canopy height) between the two water table positions. Growth was nearly halted under longer periods of surface flooding, which was not true for water table at 15 cm below the soil surface. The result of greater grain yields and dry matter after 24 days of water table at 15 cm below the soil surface than after 18 days was unexpected. This result might be because corn is more sensitive to high water tables during the early vegetative period than during the late vegetative period (Kanwar et al. 1988, Ahmad and Kanwar, 1989; Mukhtar et al. 1990). Therefore, another subject that needs to be considered is corn response to other water tables conditions during its non- or less-sensitive growth stages. The results of this study suggest that corn yield could be increased in poorly drained soils by maintaining the water table at 15 cm below the soil surface. Further studies on crop response to excessive soil water need be conducted to develop practical methods by which to maintain water table below the surface under field conditions.

Comparison of the control treatment with the other eight flooding treatments showed that each of the treatments under surface flooding or water table at 15 cm below the soil surface reduced grain yield, shoot dry matter and canopy height. The shoot dry matter loss after treatments (60 days after planting) was grater than the shoot dry matter loss at final harvest (110 days after planting). Still, both grain yield and dry matter were less than the grain yield and shoot dry-matter for control treatment. These findings indicate that treatments effects were persistent up to the final harvest and were dependent upon the level of stress.

SUMMARY

A study was conducted to determine the effects of two water-table positions and four different stress levels due to excessive wetness (during the vegetative stage of corn) on corn growth. Eighteen lysimeters (229x90x152 cm) were constructed and installed at the Iowa State University Research Center, Ankeny, Iowa. Each lysimeter was instrumented according to the requirements of data collection. Data on plant measurements such as canopy height, dry matter weight, and grain yield were collected to compare the differences in crop growth due to various stress levels. This study resulted in the following conclusions:

1. For similar values of SEW_{30}, corn growth under surface flooding was significantly different from that of under water table at 15 cm below the soil surface at all stress levels. This indicates that the concept of SEW_{30} cannot be used satisfactorily to predict corn yields.
2. The minimum stress value equivalent to SEW_{30} value of 90 cm-days at both water table positions produced no significant differences in the shoot dry matter and grain yield.
3. At harvest, growth parameters (shoot dry matter, canopy height, corn yield) showed significant differences in growth in relation to excessive soil-water conditions.
4. To predict grain yield as a function of water table position, two models were developed to minimize the error of predicting yield for smaller and larger SEW_{30} values.

5. The percentage shoot dry matter loss, due to excessive wetness, after 110 days of planting (harvest) was less than the percentage shoot dry matter loss after 60 days of planting, which indicates that corn plants have the ability to survive after the removal of stress due to excessive wetness. Nonetheless, stress effects were persistent up to harvest.

Table 4. Analysis of variance.

Source of variation	Degree of freedom	Variables		
		Grain yield	Shoot dry-matter	Canopy height
			(m e a n s q u a r e)	
Year	1	328.05	431.83	146.19
Rep. (year)	1	32.37	30.17	0.99
SEW_{30}	3	1839.87***	337.64**	917.36***
WTP	1	4238.71***	2129.48***	3966.79***
SEW_{30} X WTP	3	1281.22**	232.42*	422.92**
Error	14	147.57	90.57	85.64
Total	23			
$LSD_{0.05}$		21.27	16.68	16.21

WTP water table position
*significant at 0.10 level
**significant at 0.05 level
***significant at 0.01 level

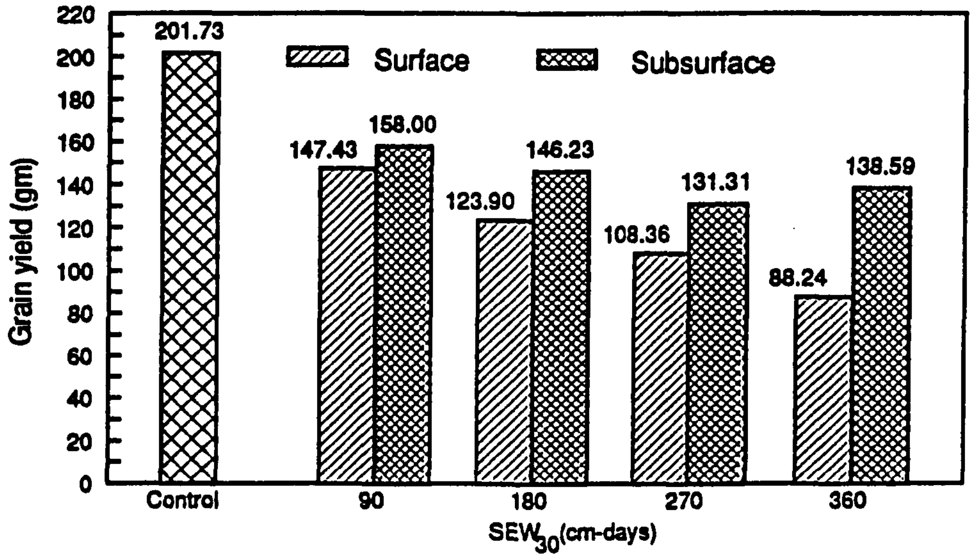

Figure 4. Grain yield as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

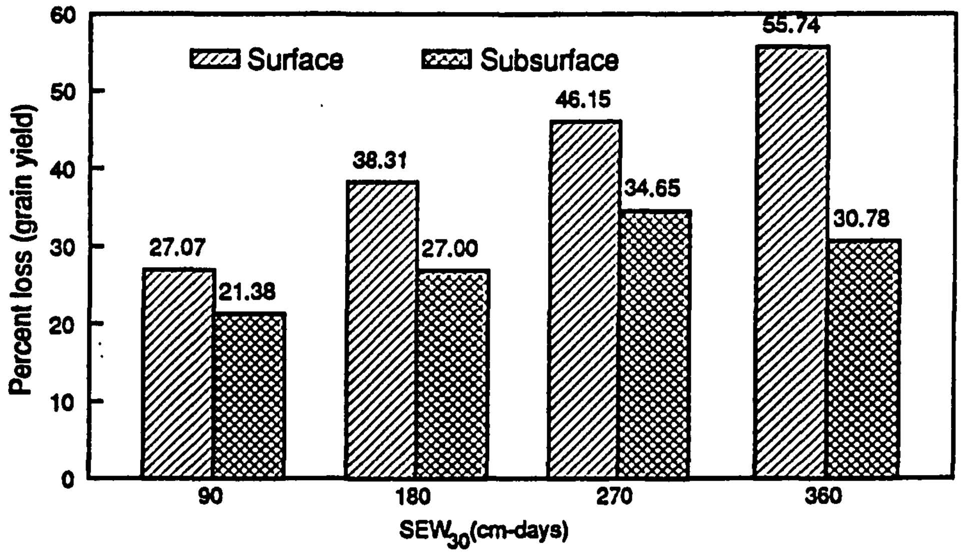

Figure 5. Percent grain yield loss as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

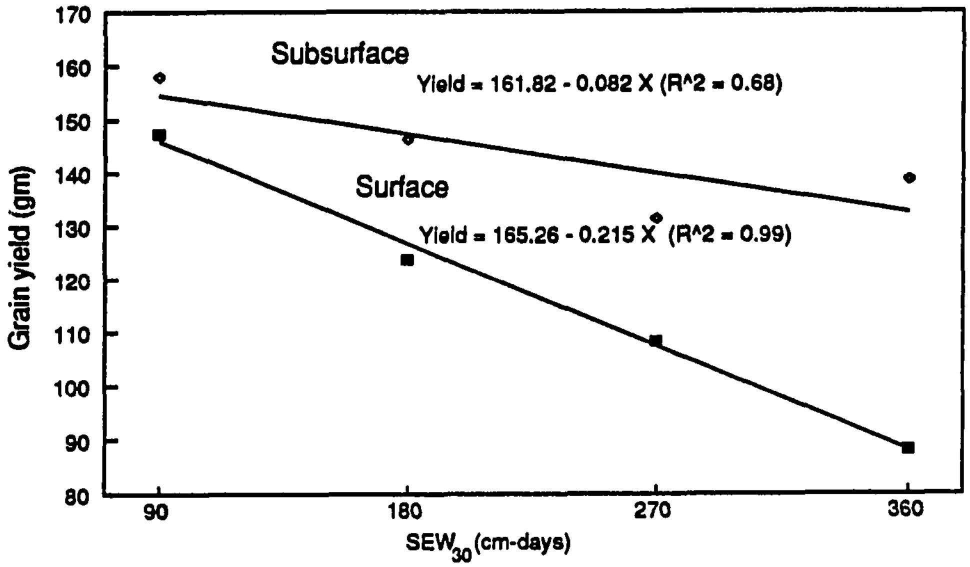

Figure 6. Linear regression equations for grain yield as a function of SEW_{30} and water table positions

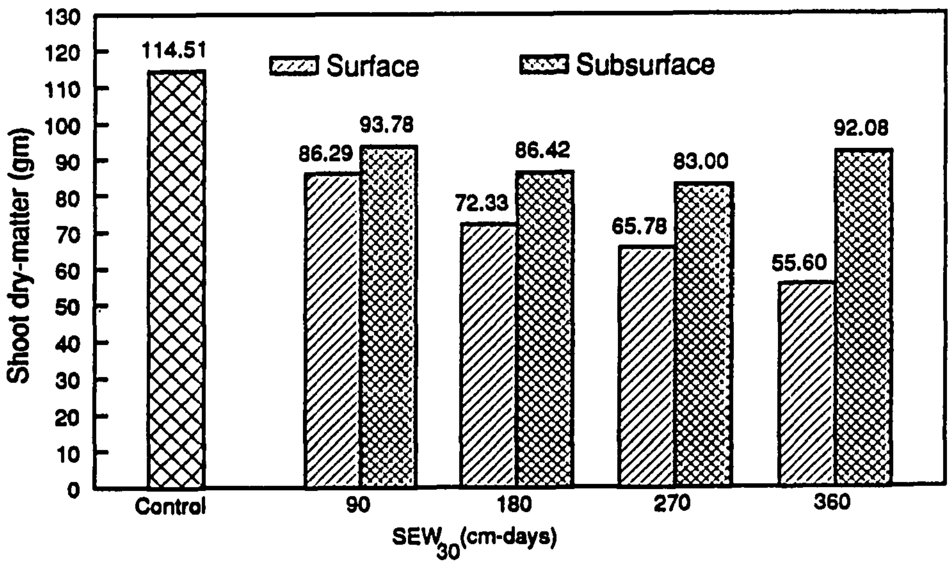

Figure 7. Shoot dry matter at harvesting as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

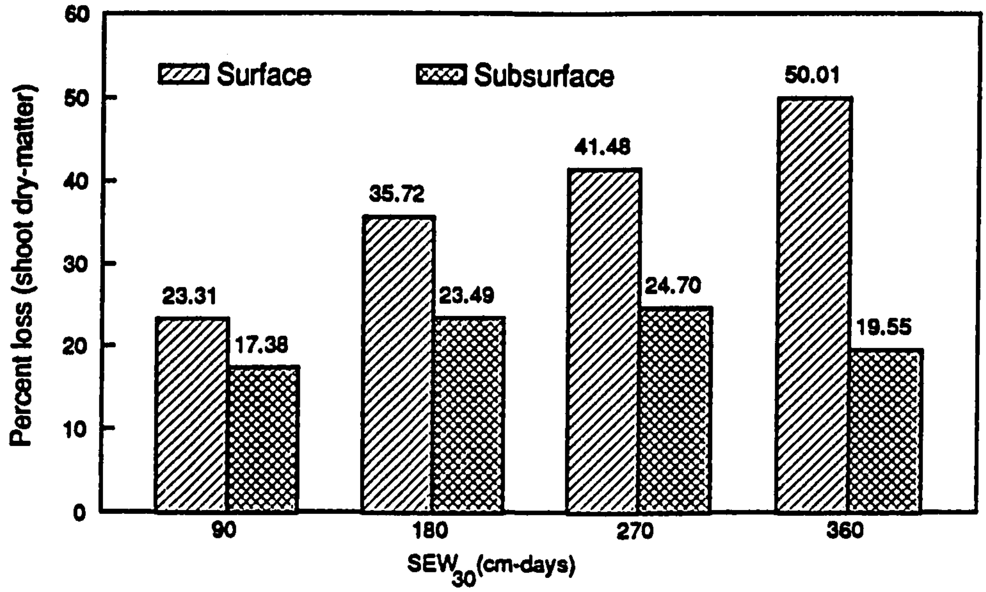

Figure 8. Percent shoot dry-matter loss in relation to control as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

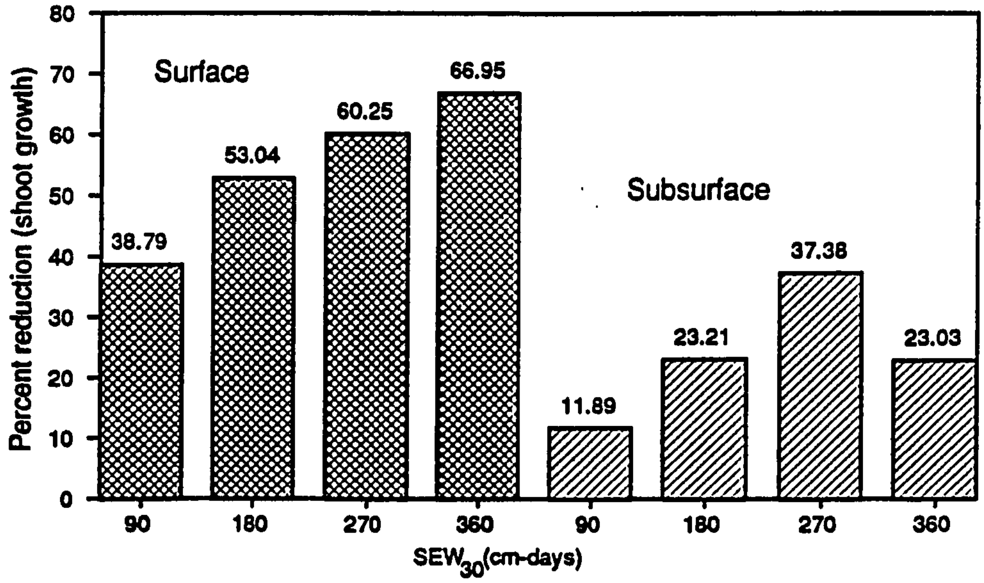

Figure 9. Percent shoot growth reduction in relation to control as a function of SEW_{30} and water table positions (surface flooding and water table at 15 cm below the soil surface)

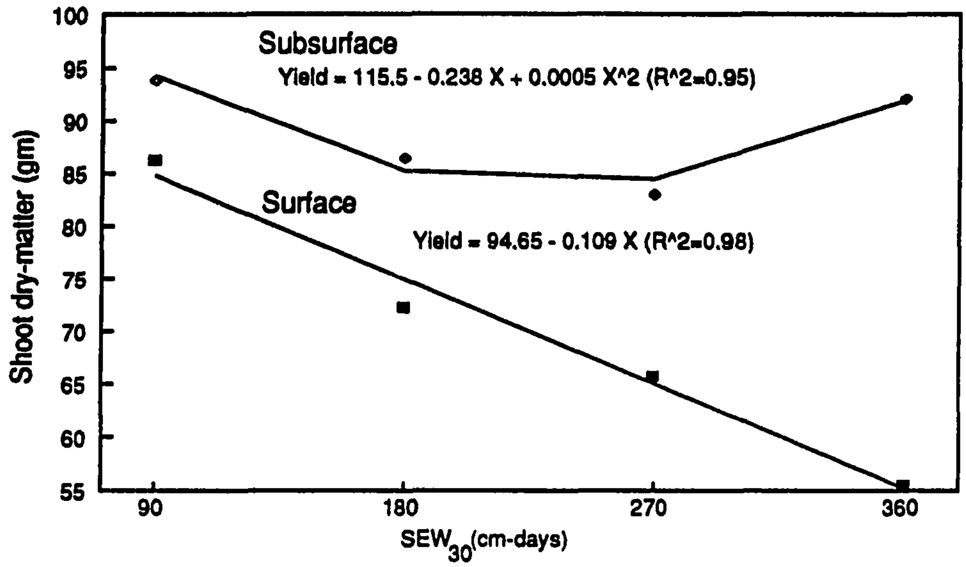

Figure 10. Regression models for dry-matter production as a function of SEW_{30} and water table positions

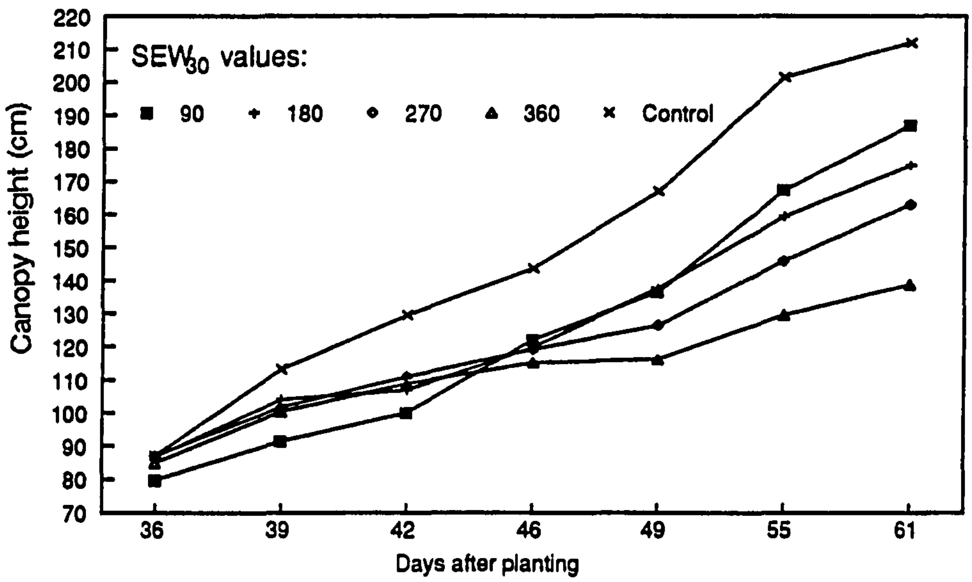

Figure 11. Canopy height as a function of SEW_{30} (surface flooding) and days after planting

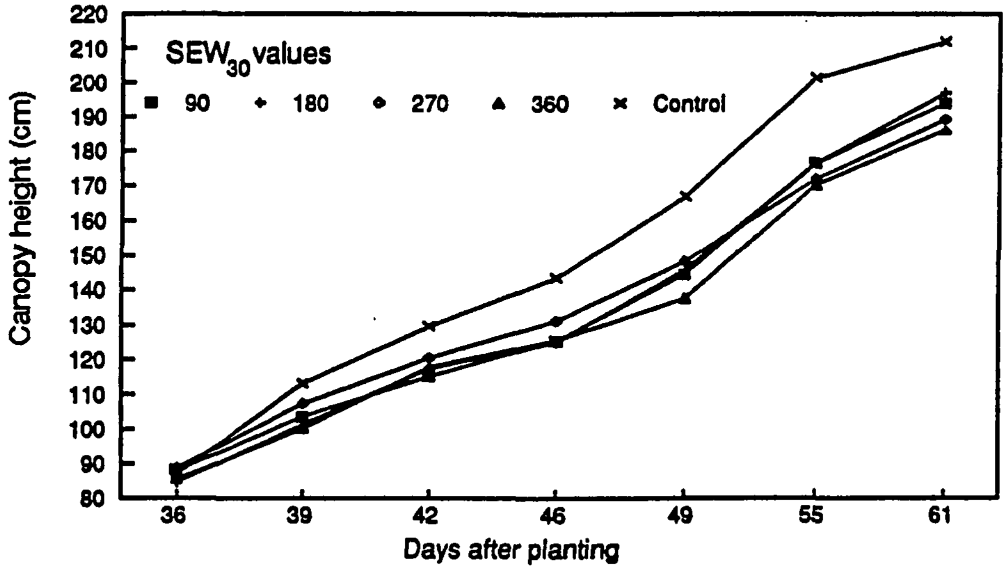

Figure 12. Canopy height as a function of SEW_{30} (water table at 15 cm below the soil surface) and days after planting

PART 4: EFFECT OF HIGH WATER-TABLE CONDITIONS ON NITROGEN USE-EFFICIENCY OF CORN

ABSTRACT

Corn (Zea mays L.) was grown in field lysimeters (229 x 152 x 91 cm) and growth chamber lysimeters (80 x 65 x 40 cm) to evaluate the effect water tables on shoot uptake of nitrogen, phosphorus, and potassium, and soil NO_3-N status. Two water table depth treatments (surface and 15 cm below the surface), each with four different durations, were imposed at the sixth leaf stage. Durations for each water table level were assigned so that the combination of water table depths and duration resulted in the same four stress levels for both water table depths as defined by the SEW_{30} stress concept. Water table depth was controlled by adding water to subsurface drains.

It was found that NO_3-N concentration in the soil solution were lower under water table at 15 cm below the soil surface conditions than under surface flooding. The N, P, and K uptakes decreased with increased duration of surface flooding. But, increased duration of water table at 15 cm below the soil surface did not decrease nutrient uptake further.

Additionally, at termination of treatments, NO_3-N loss through drainage was greater with surface flooding than with water tables 15 cm below the soil surface.

INTRODUCTION

For both economic and environmental reasons, maximizing nitrogen-use efficiency is important to farmers. Nitrogen can be lost from agricultural soils by leaching or denitrification of nitrate. Artificial drainage systems increase nitrate movement from agricultural fields in drainage water. Conversely, poor drainage accentuates nitrogen loss through denitrification. Because both leaching and denitrification can occur when soils are flooded or near saturation, these processes should be considered in the design of agricultural tile-drainage systems.

Several studies have been conducted to determine the fate of nitrogen fertilizer applied to tile-drained agricultural fields and to poorly drained fields (Kanwar et al., 1984; Kanwar, 1985; Baker and Johnson, 1977; Bengston et al., 1984; Gambrell et al., 1975b). Kanwar et al. (1984), investigating the processes of NO_3-N leaching losses with tile drainage water and annual tile flows in Iowa, reported that nitrogen leaching losses during any growing season depend on the amount of excess water removed by tile drains and on the fertilizer application rates. In another study in Iowa, Baker and Johnson (1977) concluded that artificial drainage could increase the movement of nitrates from agricultural fields. In North Carolina, Gambrell et al. (1975) reported that, because of denitrification of nitrate in the subsoil, poorly drained soils with high-water tables lose less nitrate to the drainage water than do naturally well-drained soils. Gilliam et al. (1979) conducted a study to determine the feasibility of reducing nitrate losses from tile-drained fields by controlling the water in the field to induce denitrification. They found reduction in NO_3-N losses of 1 to 40 kg/ha in a moderately well-drained soil through tile lines, and a 50% reduction in NO_3-N losses in poorly drained soils through drain ditches. Skaggs and Gilliam (1981) reported that the amount of nitrate leaving fields can be reduced by the use of controlled drainage throughout the year.

The use of controlled drainage and other water management practices is needed to reduce the amount of nitrate leaving agricultural lands. Such practices, however, cannot be applied until crop response to high water table is understood. It is, therefore, essential to study the effects of high water table conditions on plant uptake and NO_3-N leaching. The objective of this study was to investigate the effects of two water table depths (surface flooding and water table at 15 cm below the soil surface), each with four different flooding durations, corn shoot uptakes of nitrogen, phosphorous, and potassium and on NO_3-N behavior.

METHODS AND MATERIALS

This experiment was conducted in controlled environment growth chambers and field lysimeters. Field lysimeters (229 x 152 x 91 cm) were much larger in size than growth chamber lysimeters (40 x 65 x 80 cm). Details on the lysimeter construction and on the mechanisms used to maintain water tables at the desired depths are presented by Ahmad et al. (1990), and by Ahmad and Kanwar (1991). Growth chamber temperatures were programmed to simulate normal mid-Iowa temperatures between May 8 and June 29. Daily diurnal temperature patterns were based on the 30-y normal maximum and minimum temperatures for the corresponding dates, and temperatures were ramped between hourly set-points. The field site was located at the Iowa State University Research Center in Ankeny, Iowa. The soil at this experimental site is a Nicollet loam. The same soil was used in growth-chamber lysimeters.

Water Table Treatments

The nine water table treatments included one control (water table at 90 cm in field lysimeters and at 70 cm in growth chamber lysimeters) and two water-table positions (at the soil surface and at 15 cm below the soil surface), each with four different durations of flooding. Durations for water table at 15 cm below the soil surface were 6, 12, 18, and 24 days. Durations for water table 3 cm above the surface were 3, 6, 9, and 12 days. Durations were doubled for water table at 15 cm below the soil surface in consideration of the SEW_{30} stress concept (Sieben, 1964). Sieben (1964), who used the SEW_{30} to quantify stress due to excessively wet soil conditions, computed SEW_{30} values as

$$SEW_{30} = \sum_{i=1}^{n} (30 - WTD_i),$$

where WTD is the daily water table depth on day i, and n is the number of days. In this computation, negative terms are neglected, and SEW_{30} values are expressed in cm-days.

Table 1 describes treatments in terms of flooding durations and SEW_{30} values.

Table 1. Description of water table treatments

Position and flooding (days)	Depth of water table beneath soil surface (cm)	Stress levels SEW_{30} values (cm-days)	Total stress level in SEW_{30} values (cm-days)
Surface flooding			
3	0	30	90
6	0	30	180
9	0	30	270
12	0	30	360
Water table at 15 cm below the soil surface			
6	15	15	90
12	15	15	180
18	15	15	270
24	15	15	360

Each lysimeter received fertilizer at the rate of 200 kg/ha nitrogen (urea), 60 kg K (K_2O), and 60 kg P(P_2O_2). Fertilizers were dissolved in 500 ml water, and solutions were evenly applied during the second week after planting in the growth-chamber lysimeters and before planting in the field lysimeters. The water-table was maintained before and after flooding treatments at 70 cm in the growth-chamber lysimeters and at 90 cm in the field lysimeters. Corn (Pioneer 3751) plants were surface irrigated when 50% of available soil water in the upper 30 cm was depleted. Details of irrigation scheduling have already been reported by Ahmad et al., 1990 and Ahmad and Kanwar, 1991. The experimental design, both in the growth chamber and in the field, was a randomized complete block.

Data Collection Procedures

Growth chamber data

The growth-chamber experiment was repeated four times. Flooding treatments were initiated at the sixth-leaf stage of corn (26 days after planting). On the day before flooding treatments began, two plants out of six in each lysimeter were harvested for determining shoot dry matter and nitrogen contents in the plants. Additionally, soil-water samples collected from porous cups buried at three depths (20, 40, and 60 cm) were used to determine No_3-N concentration in soil-water. Soil-water samples were taken from each lysimeter on 3, 6, 9, 12, 18, and 24 days after water table treatments began. When the imposed water table treatment was completed, the lysimeter was disconnected from the overhead water reservoir and drained. The volume of the drainage water was measured and samples were taken from the drainage water for NO_3-N analyses.

After 53 days of planting, 4 plants were harvested to determine shoot dry matter and N, P, and K contents. Also, soil samples were taken from various depths for NO_3-N analyses using 12.7 mm dia soil samples. Soil samples were collected from the center of each lysimeter at 15 cm intervals. These data were used to determine residual soil NO_3-N levels for individual flooding treatment.

Field lysimeter experiment

The field experiment was conducted for two corn-growing seasons (1989, 1990) and each treatment was replicated twice. Flooding treatments were initiated at the sixth-leaf stage (36 days after planting). To determine shoot dry matter as well as N concentration in plants both before and after treatments, three plants were harvested before water table treatments began, and three plants were harvested 24 days later, when all flooding treatments were over. Twelve plants, in each lysimeter, were allowed to grow until final harvest. After harvest, plants were dried at 60°C and then grounded for chemical analysis. Plant stovers for the first two harvests were analyzed for N only; the final harvest stover was analyzed for N, P, and K.

Collection of water-sample data was similar to that of growth-chamber data, except that, after 60 days of planting, additional water samples were collected on weekly basis after all flooding treatments were terminated. Two days after final harvest, soil samples (0-15 cm, 15-30 cm, and 30-60 cm) were taken from top 60 cm of soil profile to measure residual NO_3-N.

Analysis of Shoot Dry Matter, Soil, and Soil-Water Samples

The Kjeldahl method was used to determine total nitrogen of shoot dry matter, including nitrates and nitrites (Bremner and Mulvaney, 1982), whereas methods described by Issac and Kerber (1971) were used to determine P and K concentrations of shoot dry matter. The automated cadmium reduction method (Greenbergs et al., 1985) was used to find the NO_3-N concentration in soil-water samples. The Rump and Krist (1988) method was used to extract soil water solution from soil samples so that NO_3-N concentration in soil samples could be determined by the automated cadmium reduction method.

Water Sampling Device

The water sampling device consisted of a porous ceramic cup (a clay vessel closed at one end, about 7.5-cm long, with 3-cm outer and 2.5-cm inner diameters), two transparent tygon tubes (3.5 mm), a two-holed rubber stopper (size 4), two plastic clamps, and 4- and 6-cm lengths of 4-mm outer diameter glass tubing (Figure 1). The two-holed rubber stopper was glued to the cup with a sealant. The two glass tubes were placed in the hole in the rubber stopper. One of the glass tubes reached the bottom of the cup, and the other, reached the top of the cup, acted as an air vent when the sample was removed. The two polyethylene tubes were inserted in the glass tubes and sealed with a sealant. A 60-cc syringe was used to create suction inside the porous cup one day before collecting water samples. Three of these water sampling devices were used for the growth-chamber lysimeters to collect samples from 20, 40, and 60 cm depths; two were used in the field lysimeters for collecting samples from 30 and 60 cm depths.

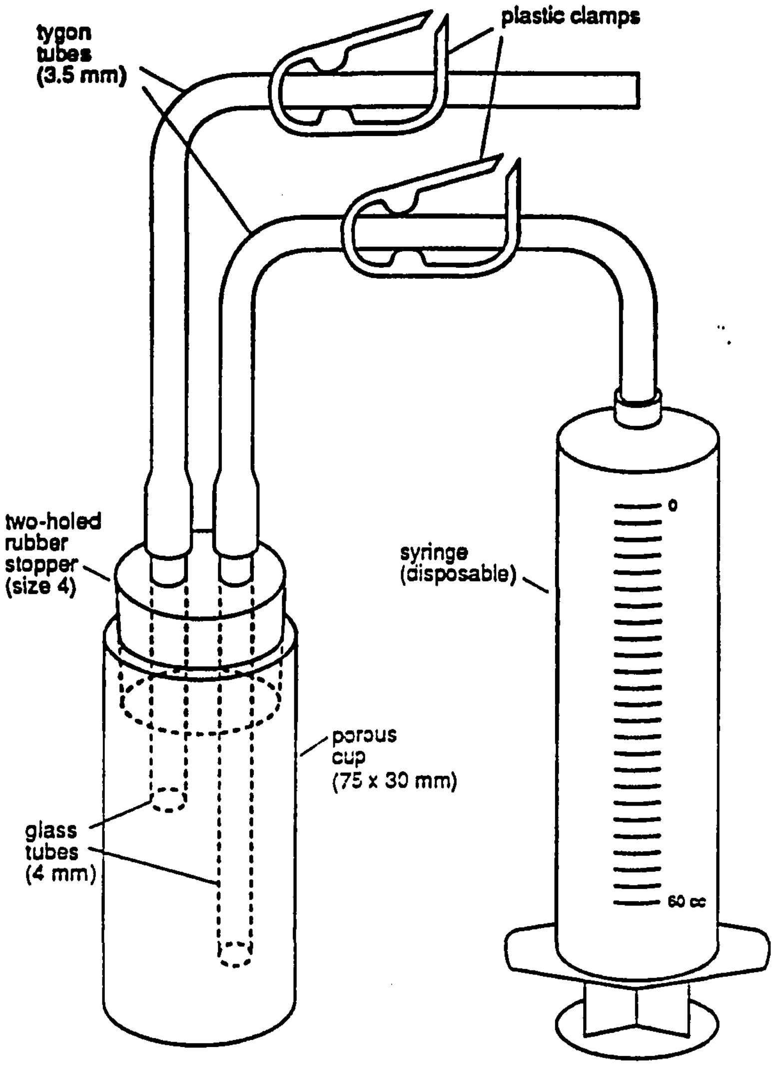

Figure 1. Soil water sample device

RESULTS

Growth-Chamber Study

Nitrate-nitrogen in soil solution

The effects of surface and water table at 15 cm below the soil surface on NO_3-N concentration in soil solution are shown in Figures 2 through 7. The average NO_3-N concentrations for identical water table treatments were calculated. For instance, the points used to develop the surface flooding lines were determined as follows: the first sampling point for each of the lines represents the average of 16 data points (all 4 surface flooded lysimeters were under treatment after 3 days of flooding for each of 4 runs) whereas the remaining points represent the average values of 12, 8, and 4 data points, respectively. The same procedure was followed for the water table at 15 cm below the soil surface lines. At 29 days after planting at the 20 cm depth, the control treatment showed about twice as much NO_3-N as did the surface or the water table at 15 cm below the soil surface treatment. These differences in NO_3-N concentrations seem to be affected by different flooding treatments. In the control treatments, surface irrigation may have caused nitrate movement to the deeper soil layers, whereas by raising the water from the bottom the flooded lysimeters may have caused the nitrate levels to stay at higher levels in the top 20 cm of the soil profile.

Figures 2 through 7 also compare the behavior of NO_3-N concentrations at different depths (20, 40, and 60 cm) for different durations of water table positions and control (where water table was maintained at 70 cm below the soil surface). Figure 2 compares the NO_3-N concentrations in soil water at 20 cm depth for 3 and 6 days of surface flooding with those of 6 and 12 days of water table at 15 cm below the soil surface. A marked increase in concentration occurred after drainage of excess water especially after 3 days of flooding, when treatments were terminated. This increase in NO_3-N concentration seems to have occurred due to mineralization of organic nitrogen and mass flow of NO_3-N from top soil to deep soil with drained water.

In contrast, a slight gradual decrease in nitrate concentration occurred during the treatment of high water table. It could thus be that a slight gradual decrease in nitrate concentration occurred as a result of nitrogen uptake and denitrification due to the anerobic conditions.

Figure 3 presents NO_3-N behavior for long durations of surface flooding (9 and 12 days of flooding) and water table at 15 cm below the soil surface (18 and 24 days of flooding) at the 20-cm depth. This figure shows that NO_3-N concentration evidenced trends similar to those discussed earlier for shorter periods of flooding, but with smaller fluctuations in NO_3-N concentration. This difference could have been caused by a decreased NO_3-N concentration due to greater denitrification under long periods of excessive soil-water conditions. An exception was that NO_3-N concentration increased only after the discontinuation of surface flooding, not after the discontinuation of water table at 15 cm below the soil surface indicating that under water table at 15 cm below the soil surface more nitrogen was taken up by plants in comparison to surface flooded conditions. The figure also indicates that, after the removal of excessive water, the increase in NO_3-N concentration at 20 cm was greater for 9 days than for 12 days of flooding.

Results of last sections indicate that NO_3-N concentration remained higher, even after long duration of surface flooding (9 and 12 days), at the soil surface than below the soil surface, and termination of treatment caused an increase in No_3-N concentration to deep soil. These results confirm that only part of the flooded soils in which nitrate is stable is the thin surface aerobic layer (Patrick et al., 1985).

Figures 4 and 5 show that NO_3-N concentration were quite small at the 40-cm depth and nearly reached zero during the first 6 days of water table treatments (surface and subsurface). Moreover, the concentration increased after the removal of excess water for surface flooding only. The only exception at the 40 cm depth was the relatively high concentration of NO_3-N for 12 days of flooding.

Figures 6 and 7 indicate that the surface flooding treatment, unlike any subsurface water table treatment, especially the removal of excess water after 3 days of flooding, increased NO_3-N concentration at 60 cm depth.

To present the behavior of NO_3-N in response to both surface flooding and water table at 15 cm below the soil surface, NO_3-N values were drawn against days of flooding (Figure 8). Figure 8 reveals that concentration of NO_3-N in soil water was greater for surface flooding than for water table at 15 cm below the soil surface at all three depths (20, 40, and 60 cm) on the third day of treatment. This difference may be due to the rapid movement of NO_3-N due to diffusion for surface flooding conditions than for water table at 15 cm below the soil surface conditions or due to higher rates of N uptake under water table at 15 cm below the soil surface. This figure indicates that NO_3-N concentration first increased from 14.8 to 16.7 mg/l and then decreased for the 20 cm depth under surface flooding. This figure also shows that, in comparison with surface flooding at the same depth (20 cm), water table at 15 cm below the soil surface resulted in a smaller NO_3-N concentration. Figure 8 illustrates that, at the 40-cm depth, NO_3-N concentrations for surface flooding treatments and for water table at 15 cm below the soil surface have fluctuations similar to those at the 20-cm depth, but that the increase in NO_3-N concentration was pronounced for the former and negligible for the latter. These results indicate that the decrease in NO_3-N concentration at the 20-cm depth was not only due to higher uptake and reducing conditions, but also due to NO_3-N leaching. For the 60-cm depth, the figure again reveals a higher NO_3-N concentration for surface than for water table at 15 cm below the soil surface.

Nitrate-Nitrogen Loss through Drained Water

Figure 9 shows the graphical relationship between days of flooding and nitrogen in the drained water for both water-table positions. The analysis of variance (Table 2) shows that NO_3-N losses through drainage water were significantly greater for surface flooding than for water table at 15 cm below the soil surface treatments. The amount of NO_3-N lost through drained water decreased with the duration of surface flooding. The maximum NO_3-N loss was 431.25 mg with drainage after three days of surface flooding, and it decreased to 84.41 mg after 12 days of flooding. Nitrate-nitrogen in the drained water decreased significantly between 3 and 6 days of surface flooding but did not decrease significantly between 9 and 12 days of flooding. When the water table was 15 cm below the soil surface, NO_3-N contents of drainage water were very low and there were no differences between different durations of flooding.

Nutrient Uptake

Plant concentrations of N, P, and K in shoot dry matter showed significant response to each of the flooding treatments (Table 2, Figures 10-12). Nitrogen uptake decreased with the increase in flooding duration and was greater for water table at 15 cm below the soil surface than for surface flooding for all durations of flooidng. Potassium concentration evidenced a relationship to flooding similar to that of nitrogen to flooding. Phosphorus concentration responded less to duration of flooding than to position of water table. Phosphorus uptake was greater for 3 days of surface flooding than for 6 days of water table at 15 cm below the soil surface.

Nitrogen uptake: Flooding had a significant effect on nitrogen uptake by the shoot, which decreased significantly between 3 and 9 days of surface flooding but not between 9 and 12 days of surface flooding. When the water table was 15 cm below the surface, nitrogen uptake decreased significantly for the flooding duration between 6 and 12 days, but not between 12 and 24 days of water table at 15 cm below the soil surface.

P Uptake: P uptake decreased significantly between all four levels of surface flooding. When the water table was 15 cm deep, P uptake decreased, although not significantly, between all four levels of water table at 15 cm below the soil surface.

K Uptake: Potassium uptake results were very similar to those of N and P uptakes (Figure 12). The only exception was that the average K uptake was greater for six days of water table treatment than for the control. The K uptake was also about six to seven times greater than the P uptake.

Nitrate-Nitrogen Residual in the Growth Chamber Lysimeters

Nitrate-nitrogen residuals (mg/lysimeters) in the soil after short- and long-term surface flooding and water table at 15 cm below the soil surface are presented in Figure 13. The smallest levels of nitrate residual (611.71 mg/lysimeters) were found in the control treatment. Figure 13 shows that residual nitrate levels increased with surface flooding. The nitrate residual level of 749.51 mg, were found under 3 days of flooding treatment and this value had increased to 2026.93 mg for 12 days of flooding. When the water table was 15 cm below the surface, residual NO_3-N was 709.33 mg for 6 days, 748.4 mg for 12 days, 1116.38 mg for 18 days, and 646.86 mg/lysimeters for 24 days of water table at 15 cm below the soil surface. Nitrate-nitrogen residual changed with depth, and it was larger for surface flooding than for water table at 15 cm below the soil surface. The largest amount of NO_3-N residual in the 0-15 cm soil layer was observed for 12 days of surface flooding (Figure 13) and the largest NO_3-N residual in the 30- to 45-cm-deep soil was observed for 6 days of water table at 15 cm below the soil surface. There could be two reasons for larger nitrate residuals with longer flooding periods: minimal plant uptake and/or high rate of mineralization after water table drainage.

Field Lysimeters

Nitrate-nitrogen in soil solution

Figures 14 through 17 illustrate the trends of NO_3-N concentration in soil solution at 55-cm and 85-cm depths against days after planting for two water table positions, surface flooding and water table at 15 cm below the soil surface. Removal of excessive water at the end of flooding treatment, especially after surface flooding, resulted in larger concentrations of NO_3-N in deeper soil and was more pronounced for small periods of flooding (i.e 3 days) than for longer periods of flooding (i.e. 12 days). Moreover, surface flooding resulted in larger NO_3-N concentrations in soil solutions than did water table at 15 cm below the soil surface.

Figure 14 compares NO_3-N concentrations (both during and after treatments) at the 55 cm depth for 3 and 6 days of surface flooding with those of 6 and 12 days of water table at 15 cm below the soil surface. Samples taken on the third day after flooding treatments began showed greater NO_3-N concentrations for surface flooding treatments than for water table depths 15 cm below the surface. Nitrate-nitrogen level decreased with days after planting. Termination of treatments (removal of excessive water) resulted in an increase of NO_3-N at the 55 cm depth, and this trend was slightly more pronounced (not significantly) for surface flooding than for water table at 15 cm below the soil surface.

Figure 15 shows similar relations for longer periods (6 and 12 surface days, and 12 and 24 subsurface days) of water table treatments. This figure reveals that NO_3-N concentrations were similar for short durations of surface and of water table at 15 cm below the soil surface, but rapidly decreased with days after planting. In comparison with the NO_3-N concentration at the 55 cm depth, that at the 85 cm depth was little more variable (Figures 16 and 17). Figures 16 and 17 also show that no flooding (control) and water table at 15 cm below the soil surface resulted in smaller NO_3-N concentrations in soil water at 85 cm depth than did surface flooding for 3 days.

Figure 18 shows the relationship between NO_3-N concentration and days of flooding (surface and subsurface). Average NO_3-N concentrations were greater for surface flooding than for water table at 15 cm below the soil surface at both depths (55 and 85 cm). But NO_3-N concentration decreased more rapidly as days of surface flooding than with days of water table at 15 cm below the soil surface.

Nutrient Uptake

Shoot uptake of N, P, and K showed significant effects of surface flooding. The shoot uptake of all three nutrients decreased with the increased duration of flooding, a relation more pronounced for surface flooding than for water table at 15 cm below the soil surface. Figures 19 through 21 show N, P, and K shoot uptakes under different durations of surface flooding and of water table at 15 cm below the soil surface.

N uptake: Nitrogen shoot uptake both at harvest after 60 days of planting and at final harvest (110 days after planting) was greater for water table at 15 cm below the soil surface than for surface flooding. The interaction between water level and stress level was significant at the 0.05 level indicating that nitrogen uptake for the two water levels responded differently to stress levels. Nitrogen uptake decreased significantly between 3 and 9 days of surface flooding, but not between 9 and 12 days of surface flooding (Figure 19). When the water table was 15 cm below the soil surface, nitrogen uptake decreased between days 6 and 12 but not between days 12 and 24.

P uptake: Figure 20 shows the graphical relation between phosphorous (P) uptake and days of flooding. The greatest P uptake occurred under control conditions. Although 3 days of surface flooding showed a greater P uptake than did 6 days of water table at 15 cm below the soil surface, P uptakes for the other durations of surface flooding were less than those for water table at 15 cm below the soil surface.

K uptake: Figure 21 shows the graphical relation between potassium

(K) uptake and days of flooding. K uptake dropped more rapidly for surface flooding (829.18 mg per plant for 3 days, to 398.94 mg/plant for 12 days) than for water table at 15 cm below the soil surface (1036.20 mg per plant for 6 days, to 762.24 mg/plant for 18 days). More K uptake was observed for 24 days than for 18 days of water table at 15 cm below the soil surface (Figure 21).

Residual Nitrate-Nitrogen in the Field Lysimeter Soil

Figure 22 shows the relation of nitrate residual to days of surface flooding and that of water table at 15 cm below the soil surface. Residuals NO_3-N did not differ between control treatment (with no stress) and short-duration surface and water table treatment, i.e 3 days of surface and 6 days of water table at 15 cm below the soil surface. Residual No_3-N increased with days of flooding and was more pronounced with surface flooding than with water table at 15 cm below the soil surface. Additionally, nitrate residual was somewhat greater in the 30- to 60-cm soil profile than in the 0- to 30-cm soil profile for both surface flooding and water table at 15 cm below the soil surface.

DISCUSSION

Surface flooding and water table at 15 cm below the soil surface had significant effects on NO_3-N concentration in the soil profile both during and after water table treatments. Drainage water from the growth chamber lysimeters contained greater amounts of nitrate after 3 and 6 days of surface than after 9 or 12 days of flooding. Maintaining water table at 15 cm below the soil surface did not result in significant amounts of nitrate in the drainage water. Moreover, nitrate loss by drainage water was very dependent upon volume of drained water. Because volume of drained water was greater for surface flooding (also with higher nitrate concentrations) than for water table at 15 cm below the soil surface, drainage from the surface flooding lysimeters caused more nitrate loss than did water drainage from the subsurface water table lysimeters.

Nitrate concentrations in the soil solution at 55- and 85-cm depths in the field lysimeters were about three times greater than those at 20-, 45-, and 60-cm depths in the growth-chamber lysimeters. The major reason for this difference might be light irrigation in the growth chamber and heavy precipitation in the field lysimeters. Excess water was pumped out of the field lysimeter with a sump pump to maintain the water table at required depths after precipitation. Movement of water downward through the field lysimeters may have carried nitrates downward.

Under both field and controlled conditions, surface flooding caused greater NO_3-N concentrations in the soil solution at all sampled depths than did water table at 15 cm below the soil surface. This finding may have been caused by low uptake of N by plants under surface flooding conditions in comparison with water table at 15 cm below the soil surface conditions. The smaller nitrate loss resulting from drainage during water table at 15 cm below the soil surface supports the hypothesis that avoiding surface flooding and keeping water about 15 cm beneath the soil surface reduces nitrate loss by drainage.

Nitrate-N concentration in drained water decreased with the increase in days of surface flooding, perhaps because of denitrification. These results agree with the findings of many other researchers (Gallichand, 1983; Gilliam et al., 1979; Skaggs and Gilliam, 1981) who have stated that loss of nutrients to leaching will be minimized if excess water does not need to be drained from the soil. Gambrell et al. (1975a,b) found similar results. These investigators stated that because of subsoil denitrification, poorly drained soils with relatively high water tables (0.3-1.5 m below the surface) lose less nitrate to drainage water than do well-drained soils. The decrease in NO_3-N loss in drained water, as well as the increase in NO_3-N uptake resulting from maintaining water table at the subsurface position, suggests that maintaining water table at 15 cm below the soil surface rather than at surface flooding, will improve nutrient use-efficiency and at the same time reduce the hazard of extensive nitrate leaching.

The two water table positions significantly reduced shoot uptake of N, P, and K. The reduction in uptake by surface flooding was greater than that caused by maintaining water table 15 cm below the surface. Meek et al. (1980), working with cotton, found that as water table depth increased (increased soil oxygen), plant uptake of all elements increased. Drew and Sisworo (1977) reported that temporarily waterlogged conditions reduced oxygen availability, which caused reduced uptake of nitrogen by roots. The major difference between plant samples from the field study and from the growth chamber was the size of the plant at a given leaf stage. Field plants were about twice as heavy as growth-chamber plants at the same leaf stage. But, despite such plant-size differences, treatment effects on uptakes were similar in both experiments. As duration of water table treatment increases, plant uptake decreases. Because concentrations of elements ranged widely and relatively greater for water table at 15 cm below the soil surface than surface flooding, it seemed that reduced uptake was the result of smaller shoots, not of reduced avialability.

This study, like many others (Gambrell et al., 1975 a,b; Gallichand, 1983; Gilliam et al., 1979) supports the hypothesis that nitrate loss can be reduced by maintaining a high-water level at a certain level below the surface. Because the suitable water table depth may differ from crop to crop, studies of different crop responses to high water tables and of methods of controlling water levels are needed.

Residual nitrate increased with days of water table treatments for both growth chamber and field lysimeters. Similar results have been reported by Kanwar et al. (1988) for poorly drained soil. Residual NO_3-

N was greater in 0- to 15-cm depths in the growth-chamber lysimeters, whereas the residual NO_3-N was greater in 30- to 60-cm depths in the field lysimeters. The reason for this difference in distribution of NO_3-N in the soil profile may have been the heavy precipitation in the field which caused nitrate to move deeper in the profile. There are three possible reasons for greater residual nitrate concentrations with longer periods of surface flooding: low N uptake by plants; nitrate reduction to ammonium and fixation on soil particles under long periods of flooding and their reversion to nitrate after termination of flooding (Patrick et al., 1985); and high rate of mineralization upon removal of the reducing condition in conjunction with low rate of N uptake.

SUMMARY AND CONCLUSIONS

Two experiments, one in small lysimeters in a controlled-environment chamber and the other in large lysimeters in the field were conducted. The purpose of these experiments was to evaluate, during and after treatment, the effects of two water table positions and four different durations, on plant-nutrient uptake and on NO_3-N behavior in the soil profile. Eighteen plastic containers (40 cm x 65 cm x 80 cm) were used in the growth chambers and 18 lysimeters (229 cm x 152 cm x 91 cm) were used in the field study. Measurements of NO_3-N concentrations in soil profile, NO_3-N content of drained water (growth-chamber lysimeters only), residual soil NO_3-N, and shoot N, P, and K contents were made for each treatment. This study resulted in the following conclusions:

1. At all sampled depths, nitrate concentration in the soil solution was smaller for water table at 15 cm below the soil surface than for surface flooding. This difference could have resulted from greater diffusion of nitrate and increased mineralization rates or small uptake under surface flooding than under water table at 15 cm below the soil surface.
2. The two water-table depth treatments had a significant effect on uptakes of N, P, and K. Nutrient uptake decreased significantly with increased duration of surface flooding. But, increased duration of water table at 15 cm below the soil surface did not decrease nutrient uptake further.
3. Imposing a water table at 15 cm below the soil surface resulted

in less loss of NO_3-N in the drainage water than surface flooding.

Table 2. Analysis of variance (growth chamber study).

Source of variation	Degree of freedom	N uptake	K uptake	P uptake	N in drained water
		(mean Square values)			
Chamber	1	19124.79	13881.53	907.69	10905.43
Rep(chamber)	2	15662.89	87974.76**	5964.54**	2199.00
Stress level	3	65700.52**	182852.28**	2012.95**	59193.58**
Water level	1	237243.38**	294518.53**	2089.33**	423899.48**
Stress level * Water lev.	3	18620.72**	29614.77	489.24	59191.28**
Error	21	3524.97	10888.56	418.46	3235.25
Total	23				

**Significant at 0.01 level

Table 3. Analysis of variance (field study, 1990 data).

Source of variation	Degree of freedom	Variables			
		N uptake (60 DAP[a])	N uptake (110 DAP)	P uptake	K uptake
		(mean Square values)			
Rep	1	11809.17	5144.11	398.80	1143.96
Stress(SEW_{30})	3	284480.61**	63409.87**	9318.24**	92018.25**
H2O lev.	1	618857.55**	5827.42**	1275.21**	362051.91**
H2O x Stress	3	78598.19*	3191.21	2038.59*	5746.15
Error	7	10353.48	1213.51	301.18	4674.17
Total	15				

[a]days after planting
**significant at 0.01 level
*significant at 0.05 level

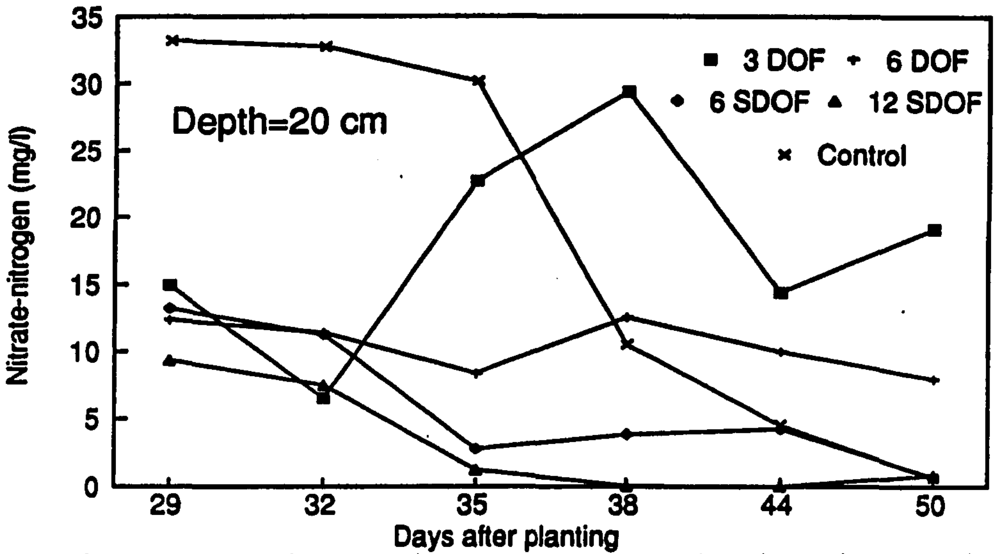

Figure 2. Average nitrate-nitrogen concentration in soil solution at 20 cm depth as a function of days of planting for surface flooding (3 and 6 days) and water table at 15 cm below the soil surface (6 and 12 days) beginning at 26 days after planting

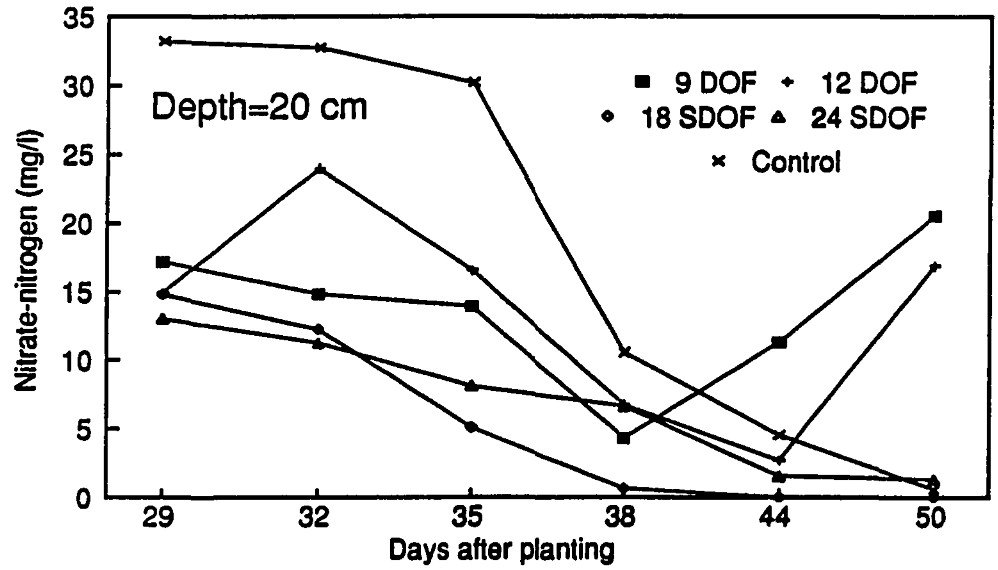

Figure 3. Average nitrate-nitrogen concentration in soil solution at 20-cm depth as a function days of planting for surface flooding (9 and 12 days) and water table at 15 cm below the soil surface (18 and 24 days) beginning at 26 days after planting

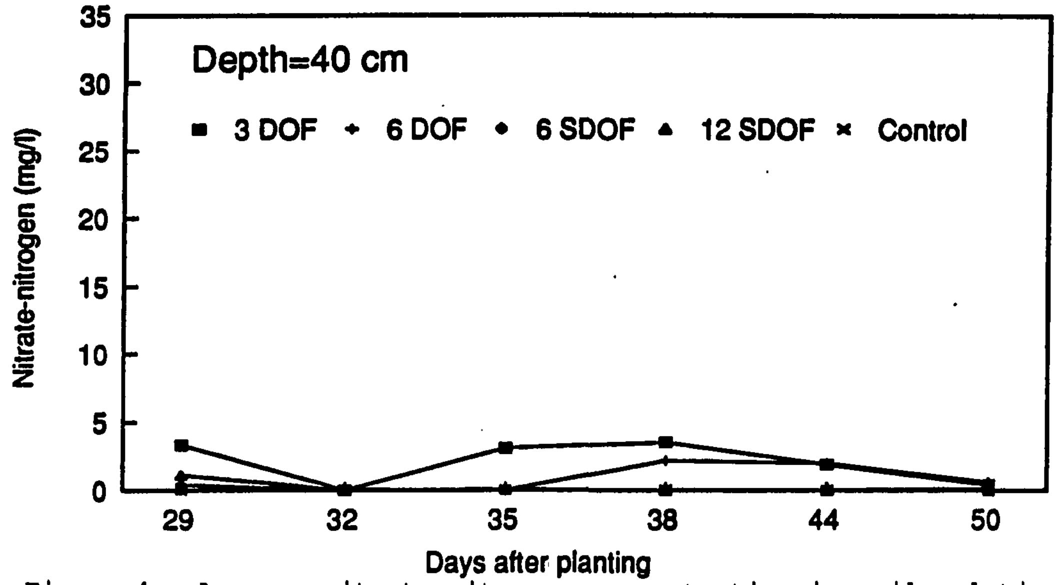

Figure 4. Average nitrate-nitrogen concentration in soil solution at 40-cm depth as a function of days of planting for surface flooding (3 and 6 days) and water table at 15 cm below the soil surface (6 and 12 days) beginning at 26 days after planting

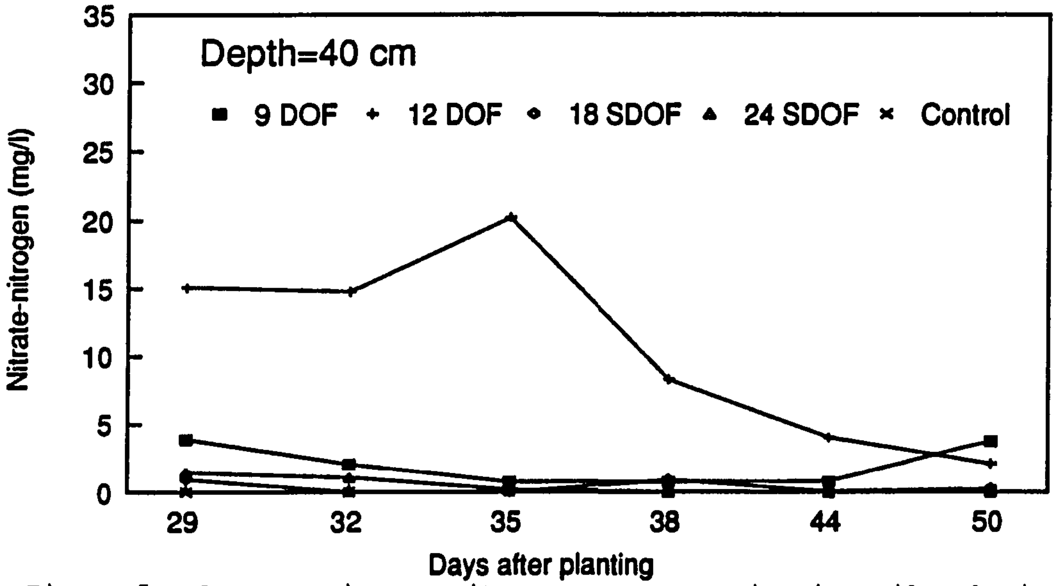

Figure 5. Average nitrate-nitrogen concentration in soil solution at 40-cm depth as a function days of planting for surface flooding (9 and 12 days) and water table at 15 cm below the soil surface (18 and 24 days) beginning at 26 days after planting

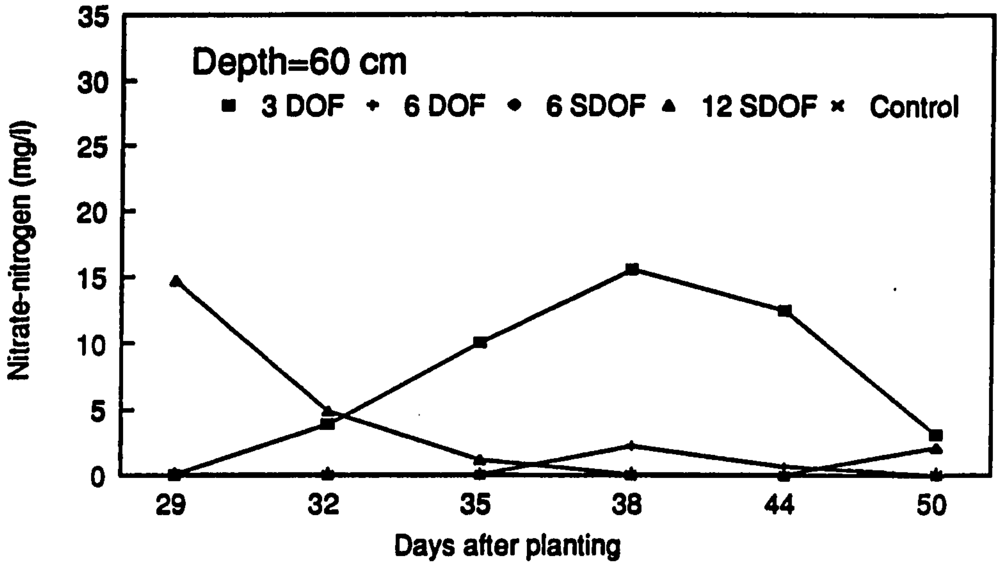

Figure 6. Average nitrate-nitrogen concentration in soil solution at 60-cm depth as a function of days of planting for surface flooding (3 and 6 days) and water table at 15 cm below the soil surface (6 and 12 days)beginning at 26 days after planting

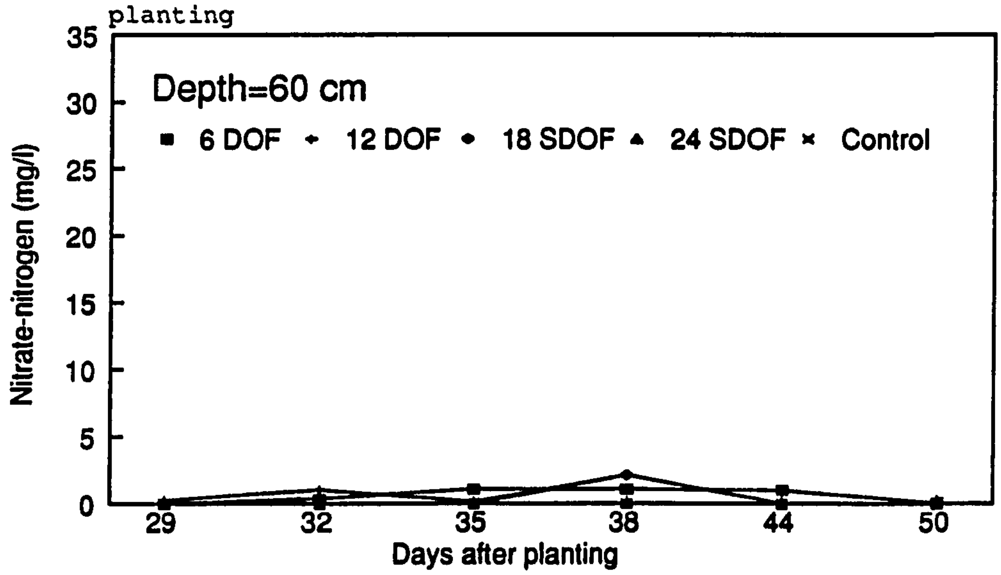

Figure 7. Average nitrate-nitrogen concentration in soil solution at 60-cm depth as a function of days of planting for surface flooding (6 and 12 days) and water table at 15 cm below the soil surface (18 and 24 days) beginning 26 days after planting

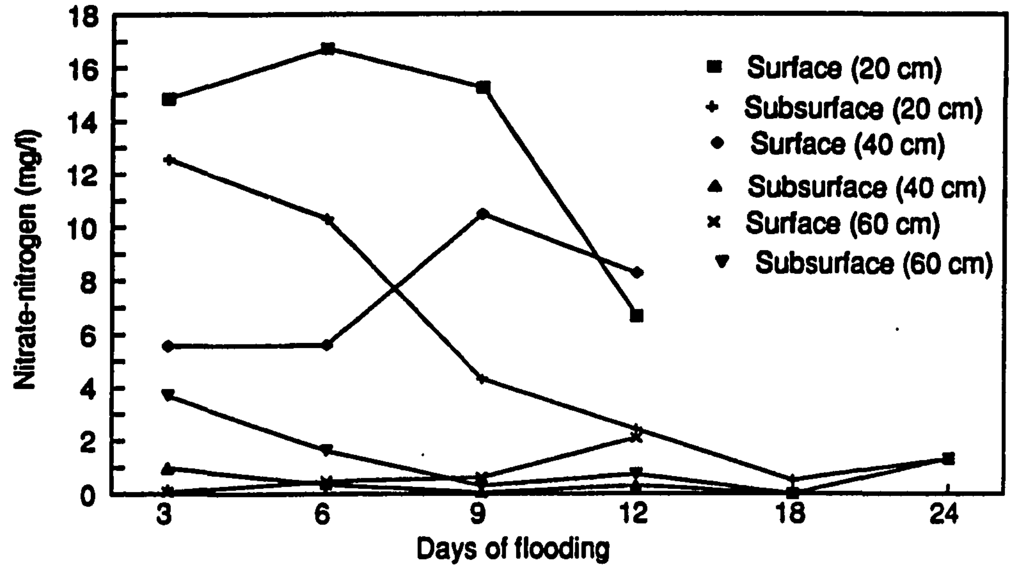

Figure 8. Average nitrate-nitrogen concentration in soil solution as a function of water table positions in growth chamber lysimeters for surface flooding and water table at 15 cm below the soil surface at the 20, 40, and 60 cm depths

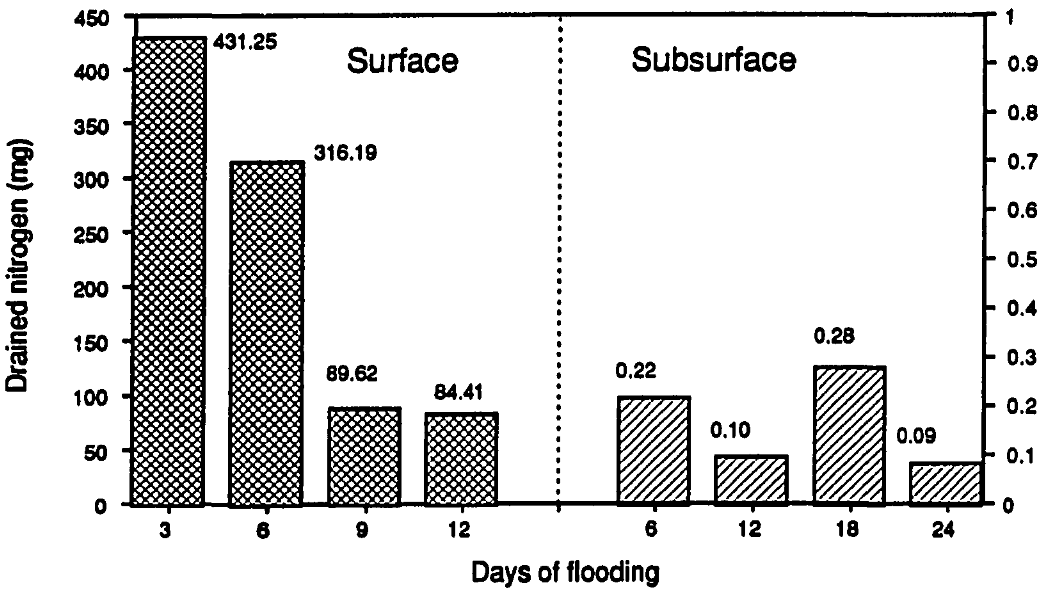

Figure 9. Average nitrate-nitrogen lost in drainage water on termination of the water table treatments

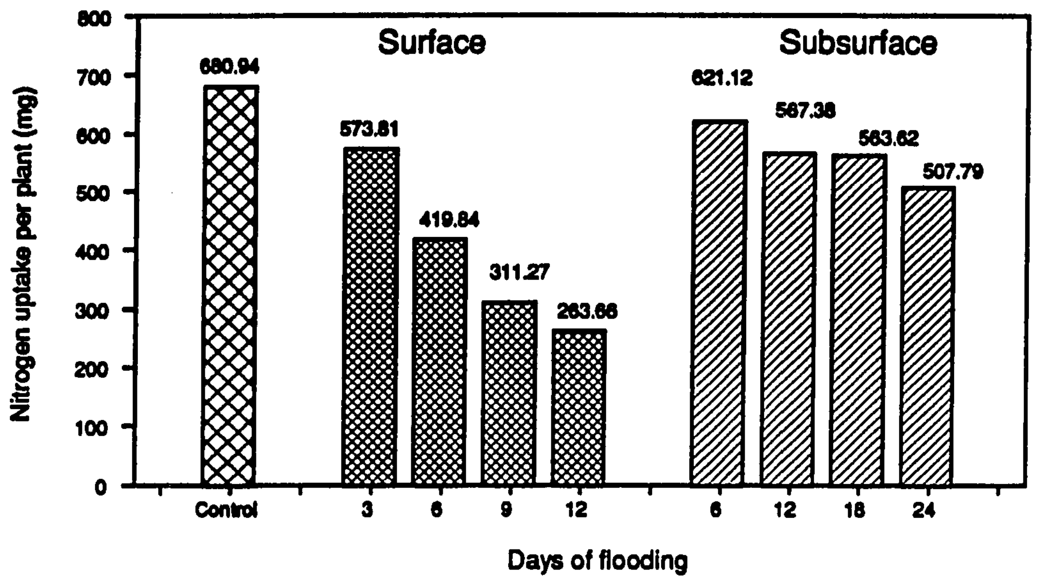

Figure 10. Nitrogen uptake as a function of surface flooding and water table at 15 cm below the soil surface in growth chamber lysimeters

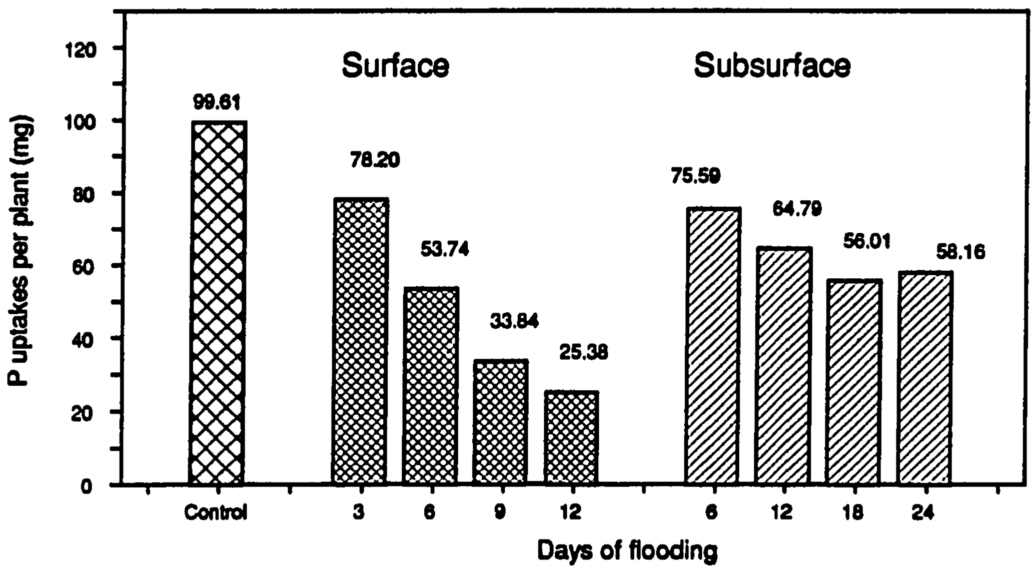

Figure 11. Phosphorous uptake as a function of surface flooding and water table at 15 cm below the soil surface in growth chamber lysimeters

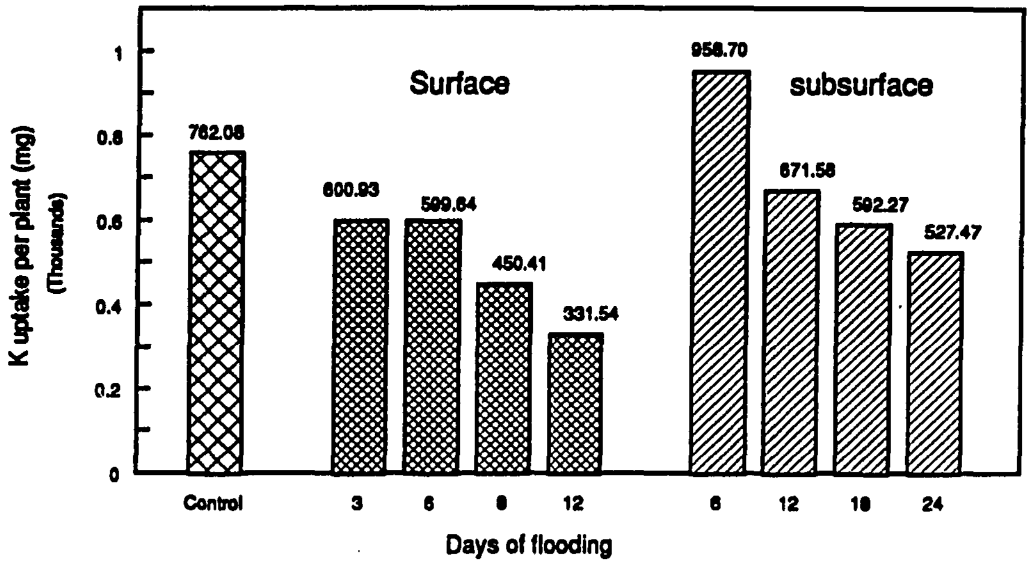

Figure 12. Potassium uptake as a function of surface flooding and water table at 15 cm below the soil surface in growth chamber lysimeters

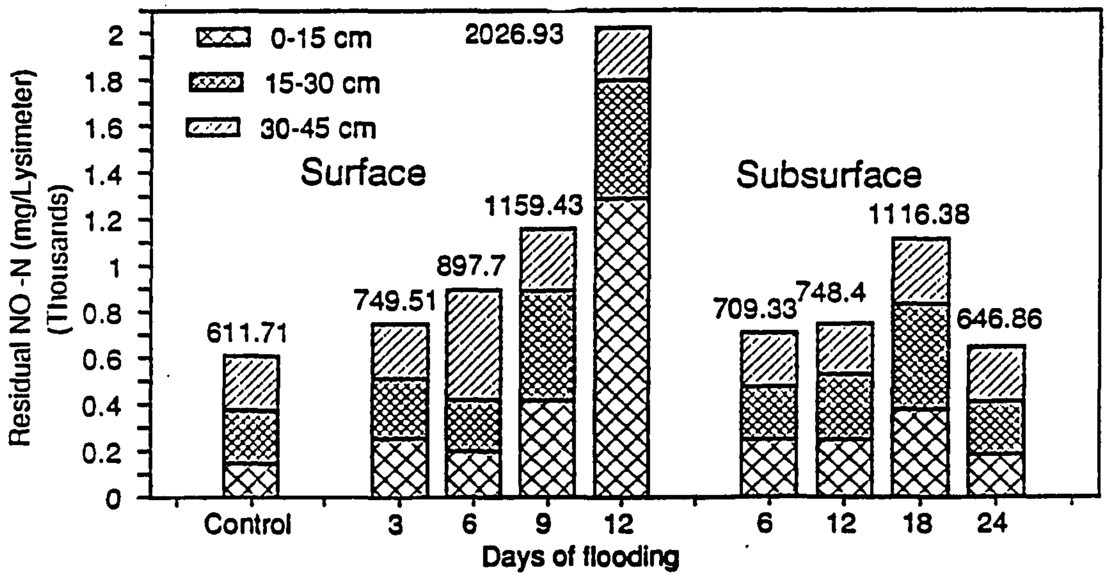

Figure 13. Residual nitrate-nitrogen in soil profile as a function of surface flooding and water table at 15 cm below the soil surface in growth chamber lysimeters

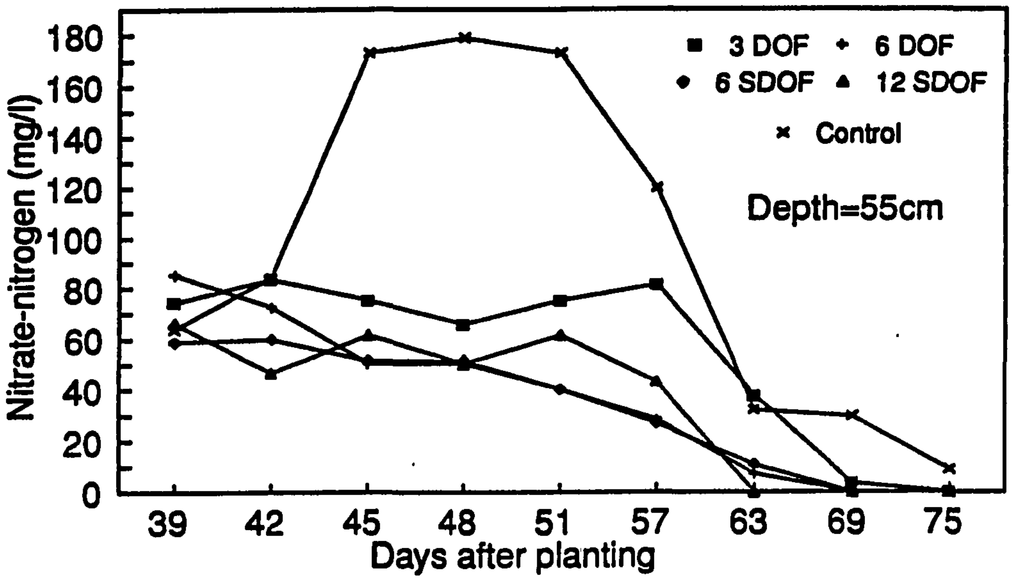

Figure 14. Average nitrate-nitrogen concentration in soil solution at 55 cm depth as a function of days of planting for surface flooding (3 and 6 days) and water table at 15 cm below the soil surface (6 and 12 days) beginning at 36 days after planting

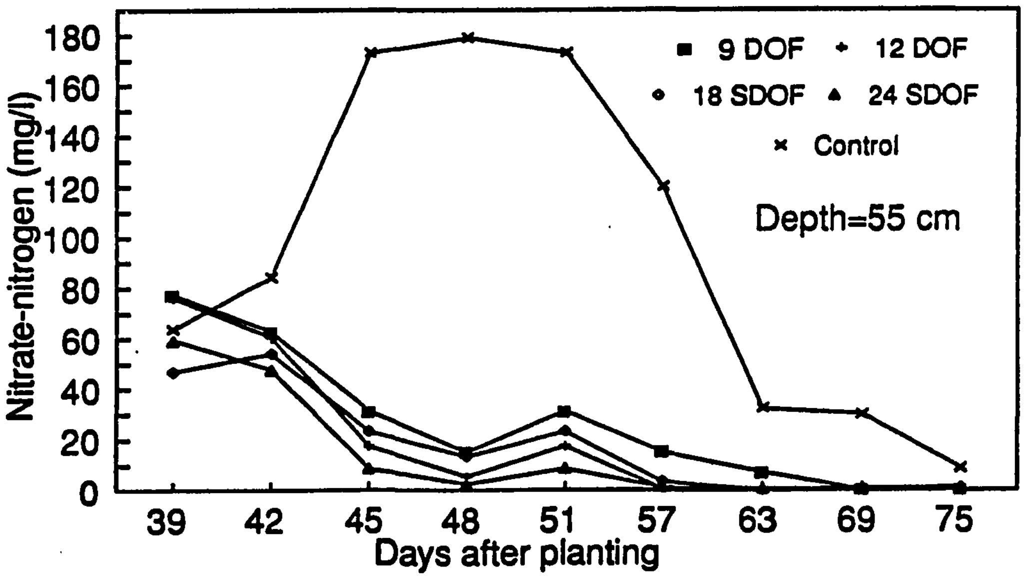

Figure 15. Average nitrate-nitrogen concentration in soil solution at 55 cm depth as a function of days of planting for surface flooding (9 and 12 days) and water table at 15 cm below the soil surface (18 and 24 days) beginning at 36 days after planting

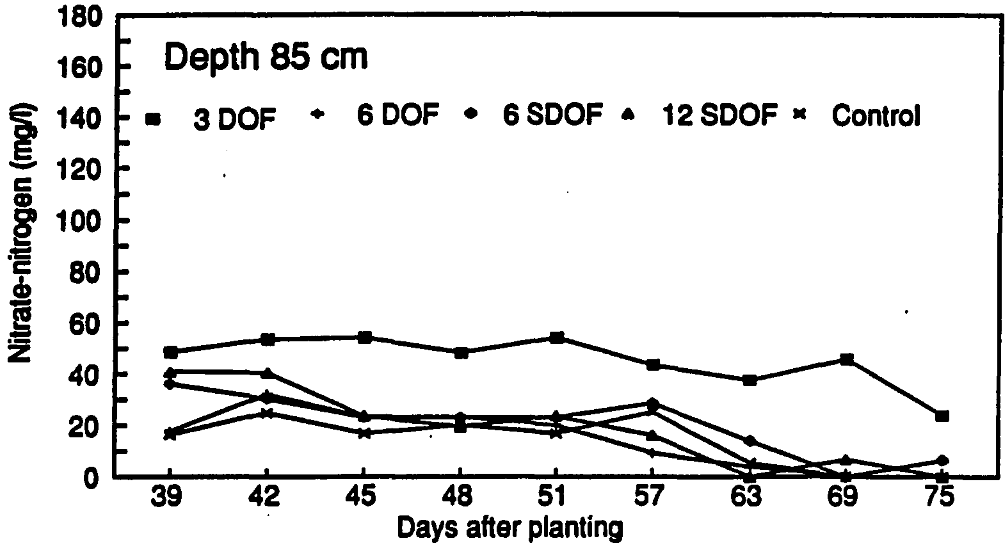

Figure 16. Average nitrate-nitrogen concentration in soil solution at 85 cm depth as a function of days of planting for surface flooding (3 and 6 days) and water table at 15 cm below the soil surface (6 and 12 days) beginning at 36 days after planting

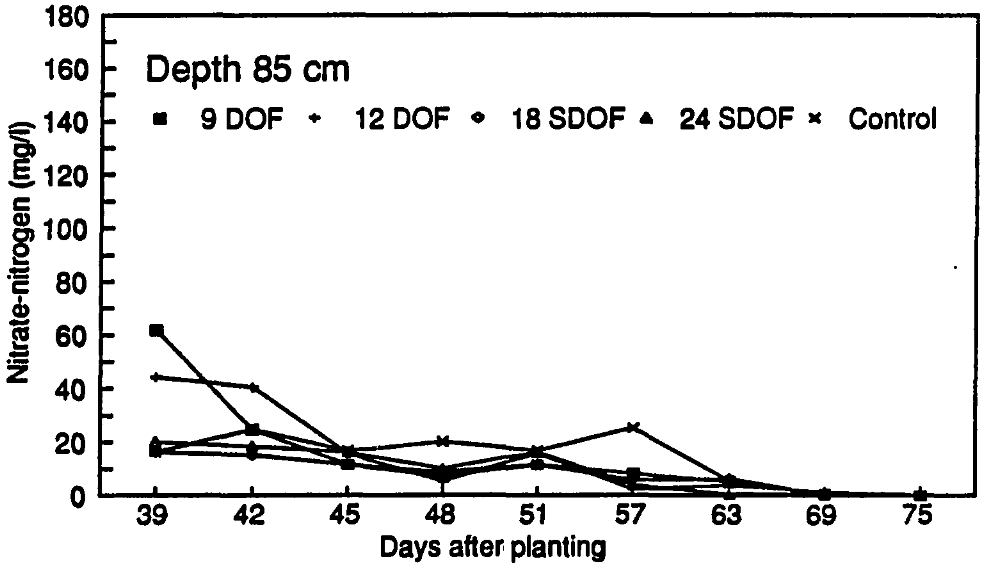

Figure 17. Average nitrate-nitrogen concentration in soil solution at 85 cm depth as a function of days of planting for surface flooding (9 and 12 days) and water table at 15 cm below the soil surface (18 and 24 days) beginning at 36 days after planting

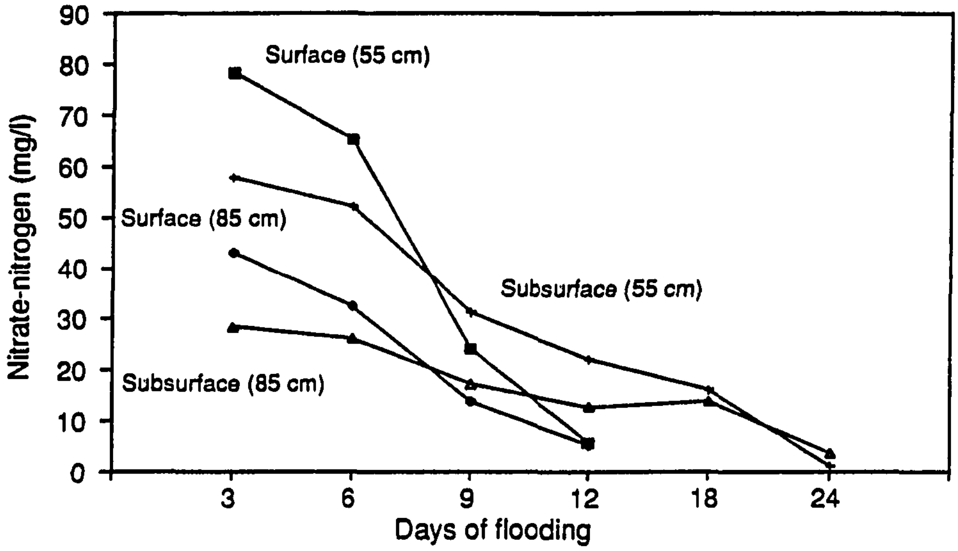

Figure 18. Average nitrate-nitrogen concentration in soil solution as a function of water table poistions in field lysimeters for surface flooding and water table at 15 cm below the soil surface at the 55 and 85 cm depths.

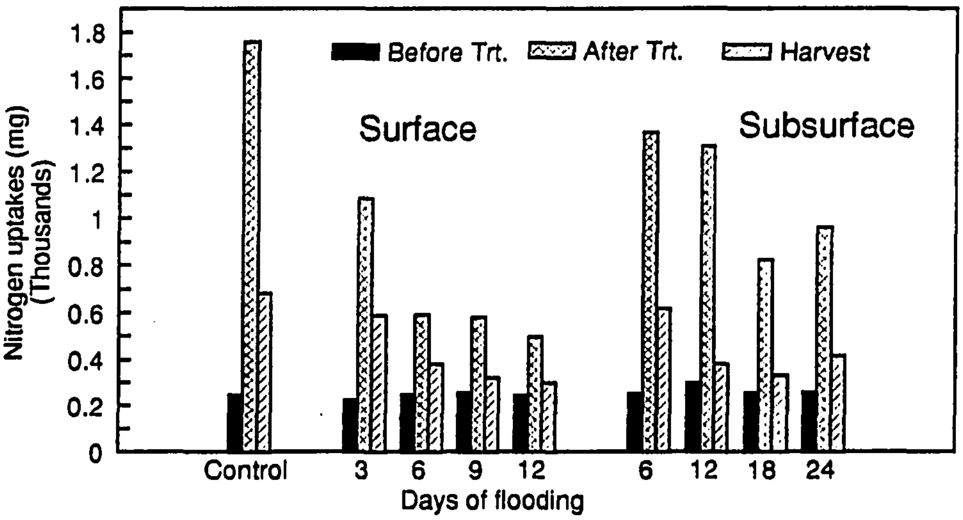

Figure 19. Nitrogen uptake as a function of days of surface flooding and water table at 15 cm below the soil surface in field lysimeters at 36, 60, and 110 days after planting

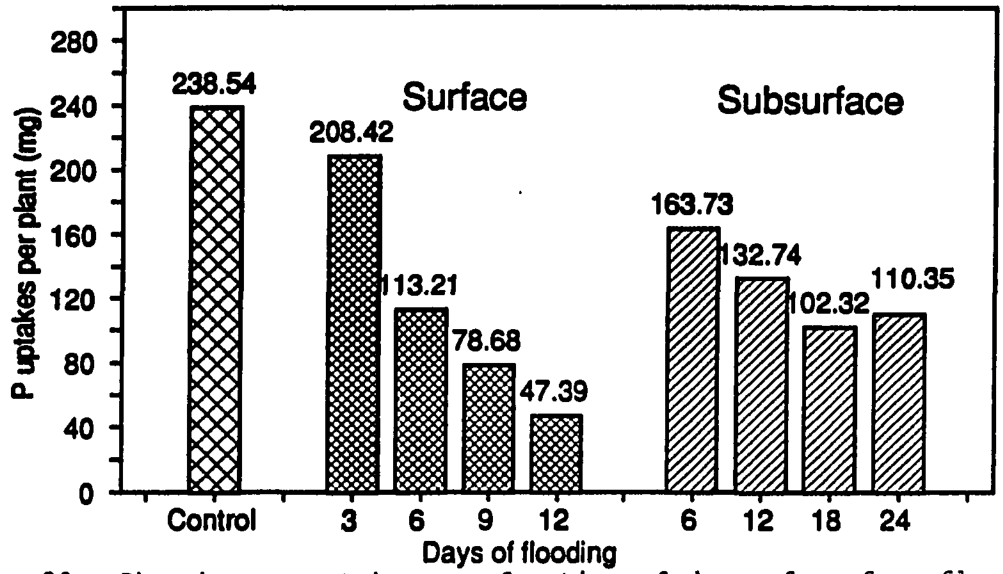

Figure 20. Phosphorous uptake as a function of days of surface flooding and water table at 15 cm below the soil surface in field lysimeters

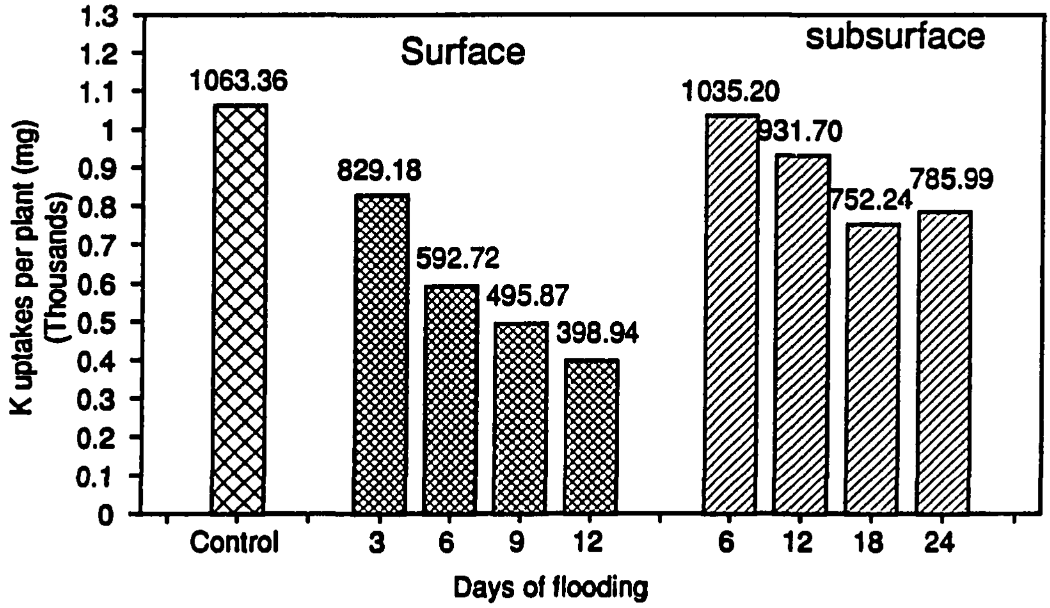

Figure 21. Potassium uptake as a function of days of surface flooding and water table at 15 cm below the soil surface in field lysimeters

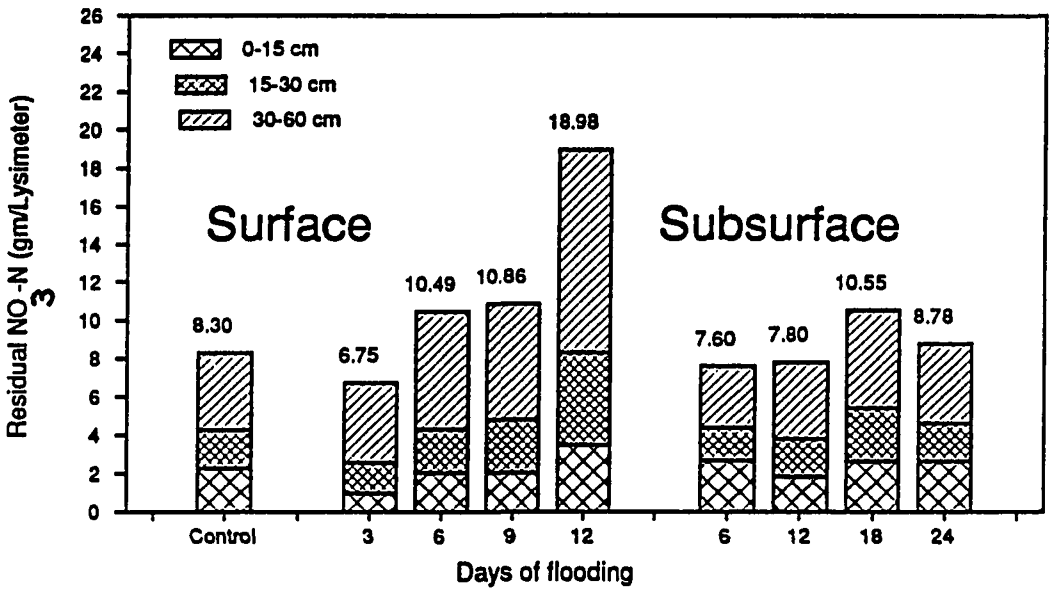

Figure 22. Residual nitrate-nitrogen in soil profile as a function of days of surface flooding and water table at 15 cm below the soil surface in field lysimeters

PART 5: UNCERTAINITY OF STRESS-DAY INDEX APPROACH TO PREDICT CROP YIELD UNDER HIGH WATER TABLE CONDITIONS

ABSTRACT

A modification was suggested to improve the Stress-day index (SDI) approach for predicting reliable yield under high water table conditions. The suggested modification was to use both crop susceptibility (CS) and crop susceptibility for water table at 15 cm below the soil surface (CSS) factors to calculate SDI values rather than only CS factors. Case studies are presented to compare the original SDI approach with modified SDI approach. It was found that the regression equation and the model developed between SDI and relative yield using only CS factors can lead to erroneous predication of yields. Results also showed that suggested modification of using both CS and CSS factors have the potential to improve the SDI and relative yield relationship.

INTRODUCTION

This paper is concerned with the quantification of high water table and with its effect on crop yield and its optimization. Optimization, in this context, means maximizing the benefit realized by achieving the more common goals of maximizing high water table efficiency or maximizing crop yield. When the water table is high that is, in the zone of stress, the removal of excess water is essential, however. To optimize the effect of high water table, it is necessary to estimate yield reduction in relation to excessive water.

The research discussed herein is concerned primarily with the stress day index (SDI) method, which relates high water table conditions to crop yield. Because of larger fluctuations in water table, the estimates produced by the SDI method are uncertain. The uncertainty level increases with both depth and frequency of water table fluctuations.

The main purpose of this paper is to discuss the uncertainty of yield production predicted by the SDI approach, about which a number of observation can be made:

1. The relationship between water table position and crop yield is characterized by quantity of water in the stress zone and not by position of water table.
2. The deficiency of the SDI approach may be so great as to significantly influence relations developed between SDI and yield in one season to another season.

3. In view of these observation, the SDI approach must be refined to include the position of water table, as well as weather factors and their effects on crop yield.

Case studies are presented in this paper to support these points. The objective of this paper is to demonstrate the need to improve the SDI approach so that it can be made applicable to predicting most probable yield under high water table conditions.

BACKGROUND

Crop Response Model for Excessive Soil Water

Many crop models have been developed to simulate physiologically-based crop growth and yield. Most of these models are for well-drained soils and are designed to predict productivity in response to deficient or optimal soil-water conditions, irrigation, fertility, and/or crop management practices. These models are not designed to predict productivity under circumstances of high water table or saturated soil.

DRAINMOD (Skaggs, 1978) is a computer model developed to simulate the performance of drainage and related water table management systems. To determine a water balance for soil profiles, the model considers rainfall, infiltration, surface runoff, drainage, storage, and deep seepage. Inputs to the model include climatological data (hourly rainfall and daily maximum and minimum temperatures); soil parameters such as hydraulic conductivity, soil water characteristics, and locations of restricting layers; crop parameters such as rooting depth vs time; and design parameters such as drain or ditch size, depth, and spacing.

This model used the stress-day index (SDI) approach to characterize the drainage requirements of crops in relation to yield. The SDI approach was introduced by Hiler (1969) to characterize the effects of deficient water stress on crop yields. This concept was proposed as a quantitative means of determining degree of stress imposed on a crop during its growing season. The same concept was used to measure the degree of stress caused to plants under excessive soil water conditions. Mathematically, the SDI approach can be expressed as

$$SDI = \sum_{i=1}^{n} (CS_i \times SD_i),$$

where SDI is stress-day index, CS is a crop susceptibility factor for i stage, and SD_i is a stress factor during i stage. The crop susceptibility factor is a function of both species and developmental stage. The stress-day factor is a measure of crop deficit/excessive stress soil water conditions. Revalo et al. (1982) equated SEW_{30} values (sum of excess water in top 30 cm deep soil) with SD_i values.

Crop susceptibility factors describe crop sensitivity to undesirable patterns of water table fluctuations at the different stages of plant growth (Revalo et al., 1982). Crop susceptibility is calculated as

$$CS_i = (X - X_i)/X,$$

where

X_i = yield from stage i with excessive moisture stress,

X = yield from plots without any moisture stress, and

CS_i = crop susceptibility value for growth stage i.

Sieben (1964) used SEW_{30} values to quantify the wet stress due to high water table conditions. He computed the SEW_{30} values as

$$SEW_{30} = \sum_{i=1}^{n}(30 - WTD_i),$$

where WTD is the daily water depth on day i, and where n is the number of days. In this computation, negative terms are neglected, and SEW_{30} values are expressed in cm-days.

SUGGESTED MODIFICATIONS TO THE SDI APPROACH

Consider the factors influencing the relationship between SDI values and yield. The former depends upon SEW_{30} values and crop susceptibility factors at respective crop growth stages. In respect to yield response, the SEW_{30} method is limited to recognizing differences between stress values obtained at two water table positions (Ahmad et al., 1990; Ahmad and Kanwar, 1991; Wesseling, 1974). For the same SEW_{30} values to occur in the same growth stage, the SDI values will have to be same, which is not true regarding the response of crop yield (Ahmad and Kanwar, 1991).

Ahmad et al., (1990) and Ahmad and Kanwar (1991) have shown that the same SEW_{30} values at two water table positions (surface and 15 cm below the surface) have a significant effect on corn yield; thus, the present SDI approach can not predict true yield response using SEW_{30} values obtained at different water table positions.

Weather is another factor potentially affecting the yield response, even under the identical water table positions; thus, crop susceptibility to high water table could differ from one season to another (Evans and Skaggs, 1984; Mukhtar et al., 1990). In fact, it can be said that anything affecting yield, in any way whatever, affects the relation between SDI and yield. Clearly, to be applicable to different locations, the SDI approach must incorporate the weather factor, which is not discussed in this paper.

How do you improve the SDI method so that it can predict most probable yield for given conditions? The answer lies in recognizing the real contribution of each SEW_{30} value obtained at different water table positions. Crop susceptibility factors determined for surface flooding do not represent crop response when water table positions are below the surface (nonflooded conditions) and produce the same SDI value for two identical SEW_{30} values. To improve the reliability of SDI values, SEW_{30} values of water table at 15 cm below the soil surface need separate coefficents or crop suscetibility values. It is difficult, however, to determine coefficient or subsurface crop susceptibility factor (CSS) for every depth from 0 to 30 cm. This concept could be improved by dividing the stress zone into possible subzones and by determining CSS factors for each zone, to minimize the error of yield prediction.

Another question is how to determine subsurface crop susceptibility, which could separate two identical SEW_{30} values and give two SDI values representing the actual yield of crop. Because the water stress of water table at 15 cm below the soil surface is less severe than that of surface flooding, to determine the CSS factors, the duration of flooding could be longer than that required for surface flooding. Experiments conducted of water table at 15 cm below the soil surface of corn for 6, 12, 18, and 24 days (Ahmad and Kanwar, 1990) suggested that for water table at 15 cm below the soil surface, the period required to determine subsurface crop susceptibility could be twice as long as the surface flooding period used to determine critical crop susceptibility. It could be that water below the surface has no adverse effects on certain crop growth stages but has adverse effects on other stages. The procedure used to calculate subsurface crop suceptibility factor will be the same as that used for surface crop susceptibilty.

A modified SDI method can be written as

$$SDI = \sum_{i=1}^{n} \sum_{j=1}^{2} (SEW_{30j} \times CS_{ij}),$$

where n is the number of sensitive growth stages, i through n and j is the number of sub zones in the top 30 cm of soil profile (j = 2 in this study).

MATERIALS AND METHODS

Using the approach suggested, the degree of improvement of the relation between SDI and relative yield was tested. The data used concerning SEW_{30}, relative yield, CS, and CSS were taken from Ahmad et. al. (1990), Ahmad and Kanwar (1991), Mukhtar et al. (1990), and Kanwar et al. (1988).

Crop susceptibility factor for 12 days of surface flooding and CSS factor for 24 days of water table at 15 cm below the soil surface during the vegetative growth stage of corn were calculated from the results of an experiment conducted in field-type lysimeter in Iowa (Ahmad and Kanwar, 1991). The CS factors for other growth stages were obtained for surface flooding from the results of another field experiment conducted in Iowa (Mukhtar et al., 1990).

Stress zones were divided into two subzones (each of 0 to 15 cm) and SEW_{30} values were calculted separately from each zone. For zone 1, when the water table was between 0 to 15 cm below the soil surface, SEW_{30} values were calculated using the relation

$$SEW_{30} = \sum_{i=1}^{n} (30 - WTD_i),$$

For zone 2, when the water table was below 15 cm from the soil surface, SEW_{30} values were calculated from the relation

$$SEW_{30} = \sum_{i=1}^{n} (15 - WTD_i),$$

Because CSS for stages other than the vegetative growth stage of corn were unavailable, only CS factors were used to caculate SDI values from SEW_{30} values both 15 cm below the surface and in the top 15 cm of the soil surface, for other growth stages. Models using only CS factors for surface flooding and using both CS and CSS factors for both surface and water table at 15 cm below the soil surface were developed to describe a relationship between SDI and relative yield.

The following paragraphs briefly summarize the experiments involved in this paper.

Controlled Flooding Experiments

Mukhtar et al. (1988) obtained crop susceptibility factors from four growth stages of corn by conducting experiments in 12, 3m x 6m field-type-lysimeters. Plots were flooded once for 10 days during each growth stage. Data on crop susceptibility factors for surface flooding were used in this article.

Ahmad et al. (1990) and Ahmad and Kanwar (1991) conducted experiments in controlled environment chambers and in field lysimeters to investigate the effects of different degrees of stress levels at both surface and water table at 15 cm below the soil surface with SEW_{30} values equivalent to 90, 180, 270, and 360 cm-days on the vegetative growth stage of corn. Yield data were obtained from the field study to calculate CS and CSS factors for the largest SEW_{30} values (360 cm-days) of surface flooding and of water table at 15 cm below the soil surface. The SEW_{30} values were also obtained from this study to develop relationships between SDI and both yield and shoot dry matter.

Naturally Fluctuating Water Table Conditions

Kanwar et al. (1988) conducted a field experiment to determine the response of corn to naturally fluctuating water table conditions in undrained soil. Fifty 15m x 15m plots were established. Each received an equivalent of 168 Kg N/ha. To permit measurement of water table depth, an observation well (180 cm long, 3.8-cm-diameter plastic pipe with perforated sides and open bottom) was installed in the center of each plot to a depth of 165 cm. The SEW_{30} and relative yield data for 1986 from this study, were used in this article.

RESULTS AND DISCUSSION

The Effect of CS and Both CS and CSS Factors on the Relationship between SDI and Relative Yield-Lysimeter Studies.

Relation between SDI and relative yield (grain)-field lysimeters

Table 1 presents the SEW_{30} values for two water table positions as well as corresponding SDI values, which were calculated by using only CS factors and by using both CS and CSS factors from the field lysimeters data. Different regression models were applied to develop the relationships between SDI values and relative yields. For both cases (using only CS factors and both CS and CSS factors), the best fitted models between SDI and relative yield were linear. The coefficient of determination was 0.49 when only CS factors were used and 0.94 when both CS and CSS factors were used. In short, the SDI relationship obtained by using only the CS factors from surface flooding treatments explained 49 percent of the variation in yield data, and the SDI relationship obtained by using CS and CSS factors from both surface flooding and water table at 15 cm below the soil surface explained 94 percent of the variation in yield data. These r^2 values indicate that the relation between relative yield and SDI improved by using both CS and CSS factors. The reason for the improved relation between SDI and relative yield is the use of CSS values. Table 1 shows that SDI values remained the same for the same SEW_{30} values of surface and water table at 15 cm below the soil surface when only CS factor was used, but that relative yield differed between water table positions, which caused poor fit between SDI and relative yield. Deviation between observed values and regressed values was calculated, and this value also showed grater variation when only the CS factor was used than when both CS and CSS factors were used.

Figure 1 illustrates the effects of CS and of both CS and CSS factors on the relationship between SDI and relative yield for field lysimeters. Figure 1 also shows linear regression equations and models for relative yield prediction as a function of SDI values for both CS factors and CS and CSS factors. This Figure reveals that for any SDI value, the model using only CS factors from surface flooding experiments yields higher relative yields than does the model using both CS and CSS factors which resulted from larger SDI values from the use of only CS factors. Thus, the use of the model based upon only the CS factor to predict relative yield might lead to erroneous predictions.

Relation between SDI and relative yield (shoot dry matter)-controlled environment chambers

The SEW_{30} values applied in the growth chamber study, the CS and the CSS factors obtained from shoot dry matter, and the relative yield of shoot dry matter are given in Table 2. This table also presents SDI values calculated when only the CS factor was used and when both CS and CSS factors were used.

To observe the effects of CS and of both CS and CSS on the SDI for shoot dry matter of corn, regression models were developed. These models show that relative shoot dry matter yield decreased linearly with SDI when using only CS and using both CS and CSS factors. Figure 2 shows both linear regression equations and models for relative dry matter yield production as a fuction of SDI. As discussed earlier, because relative shoot dry matter was greater for water table at 15 cm below the soil surface and because use of only CS factors gave the same SDI values for both water table positions, the model based on only CS factors showed poor fit to observed shoot dry matter values, which was not true when both CS and CSS values were used to calculate SDI values. The model based on only CS factors results in a coefficient of determination, r^2, equal to 0.22, which means that only 22 percent of the variation in relative shoot dry matter yield could be explained by the SDI. On the other hand, the model based on both CS and CSS factors resulted in a coefficient of determination, r^2, equal to 0.93, which means that 93 percent of the variation in relative yield could be explained by the SDI. These r^2 values indicate that the relation between SDI and relative shoot dry matter can be improved by using both CS and CSS factors. The variance calculated between observed and predicted dry matter yield was 0.26 when only the CS factors were used in comparison to the variance of .03 when both CS and CSS factors were used together, a finding which also supports the use of both CS and CSS to improve the SDI approach.

Effect of CS and Both CS and CSS Factors on the Relationship between SDI and Relative Yield for Naturally Fluctuating Water Table Conditions.

Only one set of field data from Iowa was available in the literature describing corn growth response under naturally fluctuating water table conditions rather than under controlled flooding (Kanwar et al., 1988).

The 1986 data from this study were used to study the effects of only CS and both CS and CSS factors on the relationship between SDI and relative yield. The daily SEW_{30} data were separated to give SEW_{30} values between 0 to 15 cm of the soil profile and between 15 to 30 cm of soil profile from the surface. Because Ahmad and Kanwar (1991) have only one CS factor from 12 days of surface flooding experiments during the early vegetative growth stage of corn and one value of CSS from 24 days of water table at 15 cm below the soil surface during the vegetative growth stage (both early and late) of corn, respectively, the other CS factors for late vegetative, flowering and yield formations were obtained from Mukhtar et al. (1990). Therefore, the SDI values calculated for both CS and CSS were based on CSS factors during the vegetative period only.

Table 2 shows the SEW_{30} data for surface and water table below the top 15 cm of soil profile. The SDI values were calculated using only CS factors and both CSS and CS factors. Different models were again applied to develop the relationship between SDI and relative yield. In both instances, model with best fit were linear regression models. A change in coefficient of determination was observed using CS only and both CS and CSS crop factors. Coefficient of determination, r^2, was found to be 0.88 when only CS factors were used and increased to 0.91 when both CS and CSS were used. The other change observed was in terms of model sensitivity. The model obtained by using both CS and CSS factors had 10% greater reduction in relative yield per increase of SDI value than the model obtained by using only CS factors. The reason of increased model sensitivity could be due to smaller SDI values resulted by using CSS factors. Figure 2 shows a graphical relation between SDI and relative yield. The Figure 2 also shows that the both lines has same origin but spread increases with the increase in SDI values. This means that at smaller SDI values, both models have less noticeable response to yield reduction but this difference becomes large enough to be noticeable at greater SDI values.

Because CSS value was available for only one stage probably, no significant improvement was observed in the relation of SDI and relative yield for the field data. Also, significantly larger values of SEW_{30} for flooding between 0 to 15 cm of the soil profile than the SEW_{30} value for the 15 to 30 cm of the soil profile during all growth stages could be another reason for less response to CCS factors for this field data.

SUMMARY AND CONCLUSIONS

Data from two studies (Ahmad et al., (1990); Mukhtar et al. (1990); and Kanwar et al. (1988)) were used to study the improvement of SDI approach using subsurface crop susceptibility factors. Data on excessive soil water conditions (SEW_{30}), relative yield, and crop susceptibility factors for both surface and water table experiments were collected from these studies. The relationship between SDI and relative yield was obtained using only CS factor and both CS and CSS factor. Results indicated that CS factors alone do not adequately present yield response for SEW_{30} values. The model developed for the relationship between SDI and relative yield based upon CS factors alone could lead to biased/eroneous prediction of yield under excessive wet-soil conditions. Results also showed that potential is there to improve the relationship between SDI and relative yield using both CS and CSS factors than only using CS factors.

Table 1 Data collected from field lysimeters to develop SDI and relative yield relationship.

Duration of flooding (days)	SEW_{30} values (cm-days)	CS and CSS factors	SDI values using only CS factors	SDI values using both CS+CSS factors	Relative Yield
Surface flooding		CS*			
3	90	0.56	50.4	50.4	0.73
6	180	0.56	100.8	100.8	0.61
9	270	0.56	151.2	151.2	0.53
12	360	0.56	201.6	201.6	0.42
Water table at 15 cm below the soil surface		CSS**			
6	90	0.32	50.4	28.8	0.79
12	180	0.32	100.8	57.6	0.73
18	270	0.32	151.2	86.4	0.65
24	360	0.32	201.6	115.2	0.68

*Crop susceptibilty due to surface flooding

**Crop susceptibilty due to water table at 15 cm below the soil surface

Table 2. Data collected from controlled environment lysimeters to develop SDI and relative shoot dry matter yield relationship.

Duration of flooding (days)	SEW_{30} values (cm-days)	CS and CSS factors	SDI values: using only CS factors	SDI values: using both CS+CSS factors	Relative Yield
Surface flooding		CS*			
3	90	0.81	72.9	72.9	0.59
6	180	0.81	145.8	145.8	0.41
9	270	0.81	218.7	151.2	0.26
12	360	0.81	291.6	291.6	0.18
Water table at 15 cm below the soil surface		CSS**			
6	90	0.34	72.9	30.6	0.76
12	180	0.34	145.8	61.2	0.68
18	270	0.34	218.7	91.8	0.67
24	360	0.34	291.6	122.4	0.66

*Crop susceptibilty due to surface flooding

**Crop susceptibilty due to water table at 15 cm below the soil surface

Table 3. Values of sum of excess water and stress day index (SDI) for corn season of 1986 at Woodruff, near Ames, IA

Well #	SEW (0-30)	SEW (0-15)	SEW Total	SDI (CS)	SDI (CS+CSS)	Yield (Kg/ha)	Relative Yield
1	195.83	31.27	227.10	69.05	66.65	4583.93	0.81
2	200.32	47.67	247.99	75.69	71.95	5821.36	0.86
3	259.2	118.70	377.90	123.75	109.83	5724.30	0.84
4	275.59	111.31	386.90	123.22	109.47	4889.28	0.72
5	752.58	235.62	988.20	339.36	299.79	4133.46	0.61
6	558.4	177.00	735.40	274.07	242.53	4452.52	0.66
7	320.9	189.60	510.50	197.38	176.17	5497.33	0.81
8	61.92	91.28	153.20	60.41	48.85	6434.98	0.95
9	42.3	14.00	56.30	31.53	28.17	6602.44	0.97
10	68.7	84.80	153.50	85.96	65.61	6380.02	0.94
11	145.5	32.00	177.50	52.97	47.68	4983.76	0.73
12	167.1	36.30	203.40	57.61	52.64	5354.16	0.79
13	327.9	108.80	436.70	152.48	136.07	5054.98	0.74
14	509.33	187.27	696.60	263.65	239.17	3391.29	0.50
15	955.61	302.39	1258.00	464.76	522.94	2361.26	0.35
16	572	187.00	759.00	281.35	250.65	3780.70	0.56
17	459.5	117.00	576.50	237.3	209.89	4651.77	0.68
18	17.9	50.80	68.70	37.92	25.73	6302.98	0.93
19	41.7	68.30	110.00	61.6	45.21	5433.06	0.79
20	20.9	64.70	85.60	47.94	32.41	5942.51	0.87
21	30	0.00	30.00	16.8	16.8	5639.87	0.83
22	87.37	69.46	156.83	65.09	54.51	4853.06	0.71
23	428.7	251.80	680.50	278.73	245.3	3140.53	0.46
24	1073.57	329.53	1403.10	527.8	488.71	1247.36	0.18
25	1038.07	406.39	1444.46	540.84	489.53	1001.06	0.15
26	710.9	313.27	1024.17	412.69	366.64	2959.30	0.44
27	296.18	94.70	390.88	192.59	172.86	4477.30	0.66
28	0	4.80	4.80	2.69	1.54	6343.31	0.93
29	0	0.00	0.00	0	0	6743.42	0.99
30	0	0.00	0.00	0	0	6794.48	1.00
31	170.37	55.47	225.84	63.55	57.57	5722.49	0.84
32	176.31	51.50	227.81	71.26	58.89	5484.88	0.81
33	411.9	255.54	667.44	243.14	192.63	3999.05	0.59
34	656.29	168.09	824.38	311.74	286.21	3281.43	0.48
35	1063.6	197.26	1260.86	495.87	471.55	2540.89	0.37
36	525.85	250.54	776.39	338.52	309.75	3573.00	0.53
37	0	88.60	88.60	41.48	25.49	5722.20	0.85
38	0	0.00	0.00	0	0	6758.95	0.99
39	0	0.00	0.00	0	0	6606.75	0.97
40	0	0.00	0.00	0	0	6577.55	0.97
41	34	9.20	43.20	20.01	19.55	6015.50	0.89

Table 3. Continued

Well #	SEW (0-30)	SEW (0-15)	SEW Total	SDI (CS)	SDI (CS+CSS)	Yield (Kg/ha)	Relative Yield
42	52.3	53.00	105.20	38.97	34.76	5815.00	0.86
43	194.73	70.77	265.50	89.37	79.86	5227.13	0.77
44	406.76	143.89	550.65	200.07	176.75	4509.04	0.66
45	641.7	148.00	789.70	296.36	273.01	3844.24	0.57
46	346.75	245.80	592.55	247.1	216.43	4179.98	0.62
47	19.4	86.00	105.40	59.02	38.38	5927.32	0.87
48	0	8.70	8.70	4.87	2.78	6454.97	0.95
49	0	0.00	0.00	0	0	5454.86	0.80
50	0	0.00	0.00	0	0	5122.84	0.75

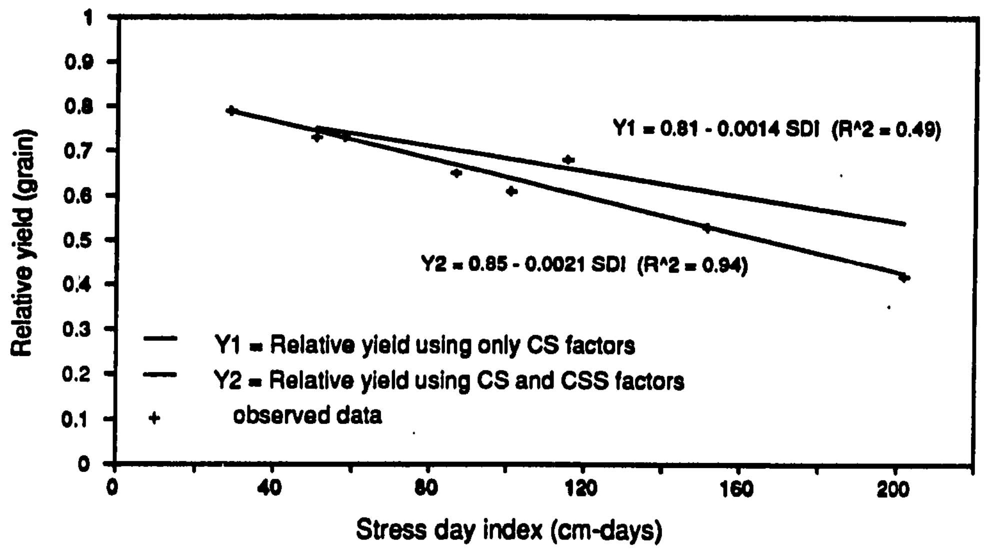

Figure 1. Linear regression models between relative grain yield and stress day index as a function of CS and both CS and CSS factors for field lysimeters

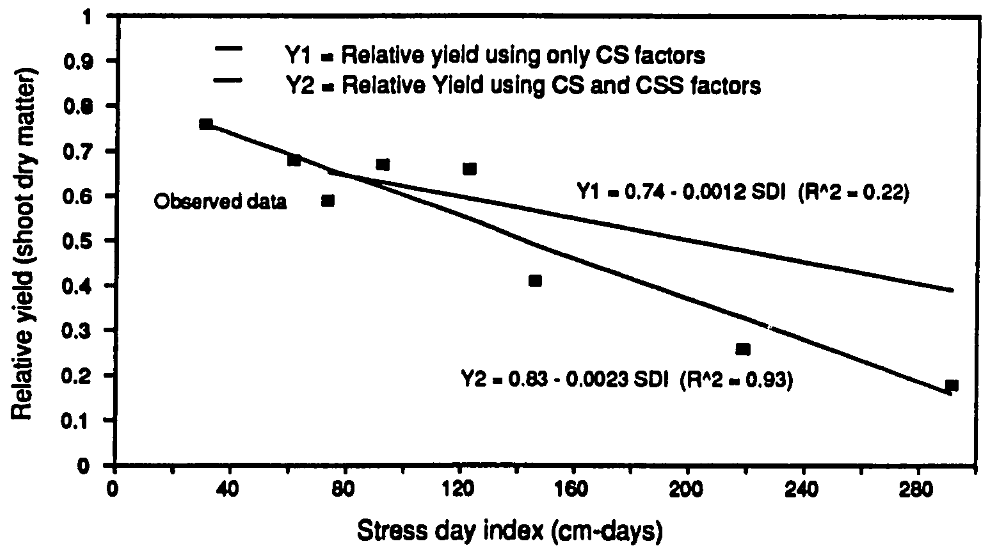

Figure 2. Linear regression models between relative shoot dry matter and stress day index as a function of CS and both CS and CSS factors for controlled environment chambers

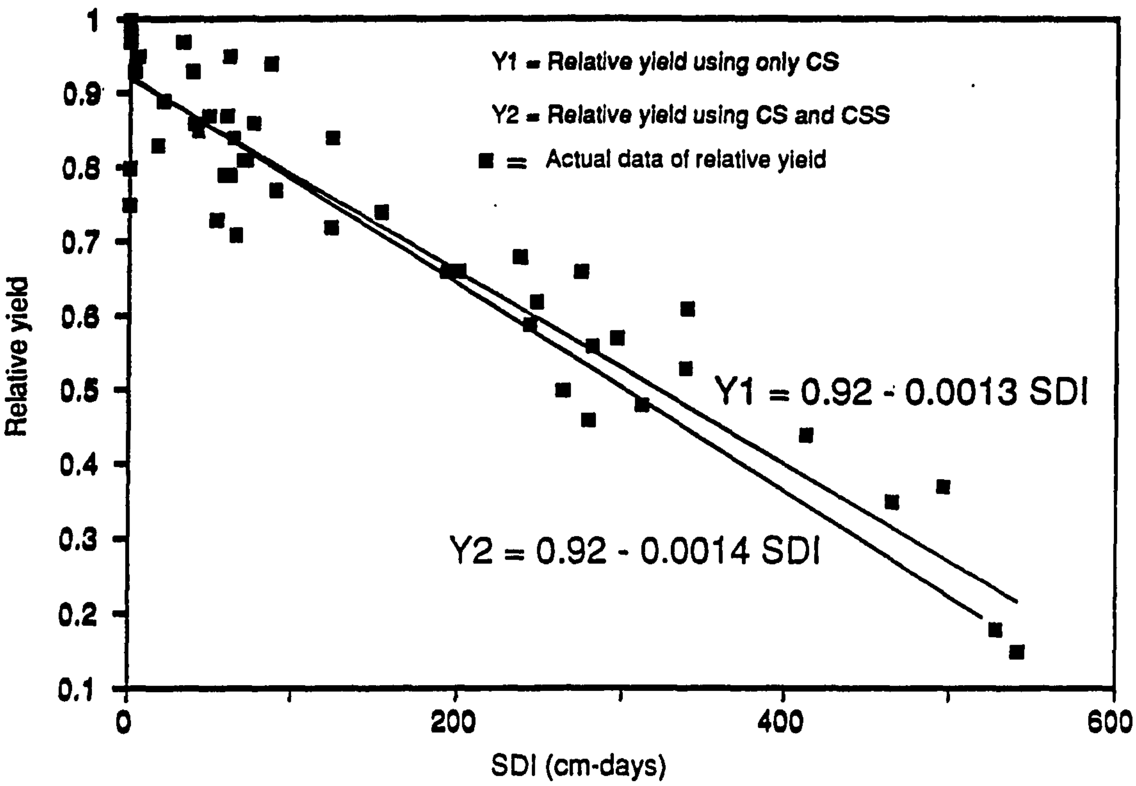

Figure 3. Linear regression models between relative grain yield and stress day index as a function of CS and both CS and CSS factors for field conditions

RECOMMENDATIONS FOR FUTURE WORK

This study reports the effects of two water table positions (at the surface and at 15 cm below the soil surface) on growth and yield during the vegetative growth stage, the most sensitive developmental stage of corn. It was observed that, compared with water table at 15 cm below the soil surface, surface flooding resulted in significant reductions in both growth parameters and grain yield of corn. It was also observed that both growth and yield of corn decreased between 6 and 18 days of water table at 15 cm below the soil surface but increased between 18 and 24 days of surface flooding.

On the basis of these observations further studies should be conducted to determine corn response to high water table for each of the other possible developmental stages because corn and many other crops may require much water during other stages if yield is to increase. The water table position causing stress at one growth stage might be quite suitable at another. Thus, further studies are needed to know when, where (at what depth) and how long a high water table causes no damage to a crop and increases yield.

The literature contains subirrigation studies establishing water at a particular depth and maintaining this level throughout the growing season. Nonetheless, few studies have been conducted exclusively of maintaining water table below the surface during the different growth stages. Such information would be important in the design of a control-type drainage system including subirrigation which I consider an important future need.

Additionally, nitrate efficiency was studied for different durations of surface and water table at 15 cm below the soil surface. Results for the water table at 15 cm below the soil surface indicated a significant reduction in nitrate loss through drainage. Again this suggests that further studies need to be conducted to develop practical methods for maintaining water at required positions below the soil surface rather than permitting free drainage of excess water. Such studies might enhance the productivity of poorly drained soils and control nitrate losses to water sources, which is a danger to the environment, to stream life and to precious groundwater resources.

Studies are also needed to determine plant nutrient uptake in response to levels of N applied to different depths and durations of high water tables. This could be another criterion to use in determining when, where and how long a high water table should be maintained to reduce nitrate loss through the drainage system while ensuring high plant nutrient uptake.

To optimize excessive soil water conditions, many studies have been conducted to characterize the relation between stress day index and relative yield. Stress day index is a product of SEW_{30} and crop susceptibility. In the present study, it was found that the SEW_{30} concept does not adequately predict crop response to different water table depths.

Limitations of the SEW_{30} concept compromise the SDI method in as much as two identical SEW_{30} values, one obtained at 15 cm below the surface and the other for surface flooding, in the same developmental stage, will yield identical SDI values for significantly different yields. Clearly, this concept needs to be improved. It seems that the crop susceptibility value obtained for surface flooding does not represent the real response of corn to water table at 15 cm below the soil surface. It is suggested that, instead of using one, use two crop susceptibility factors, one for surface flooding and other for water table at 15 cm below the soil surface, to improve SDI values. To test this approach thoroughly, further studies are required to determine the crop susceptibility factors for water table at 15 cm below the soil surface at different stages of corn.

Another aspect of this study involved using a minirhizotron to determine root response to both surface flooding and water table at 15 cm below the soil surface. The results of this part of the study suggest that more work is required to develop suitable methods of installing observation tubes to obtain representative photographic samples of roots.

GENERAL SUMMARY

The major objective of this study was to determine the effects of two water table positions (surface flooding and water table at 15 cm below the soil surface) on soil nutrient behavior in the soils and on growth and yield of corn. Experiments were conducted in controlled environment chambers and in field lysimeters to determine the effects of four different durations of surface flooding (3, 6, 9, and 12 days) and water table at 15 cm below the soil surface (6, 12, 18, and 24 days) on the vegetative growth stage of corn.

Eighteen field lysimeters (229 x 65 x 81 cm each) and eighteen growth chamber lysimeters (80 x 65 x 81 cm each) were designated and instrumented for this study. Field lysimeters were constructed by bolting five 6.2 mm-thick plastic sheets (four for each side of a rectangular box and one for the bottom) together with aluminum angle irons. The corners of the lysimeters were treated with silicone building and glazing sealant to make them waterproof. Plastic containers were utilized with the growth chamber lysimeters.

To raise and lower the water table in the lysimeters, water level control mechanisms were developed. A water sump consisting of a 183 cm-long PVC pipe, 38 cm in diameter, with a adjustable float system was used in each of the field type lysimeters. The float system used in the growth chamber consisted of small bucket-type reservoir, a transparent polyvinyl tube, and a float. The float system of the growth chamber was portable and changed the water level inside the container by changing its position on a steel shelf; water table could thus be adjusted according to the needs of the study.

In both experiments, instrumentation was provided according to the needs of the data collection procedures. To determine the nitrate contents of the soil water solution, two suction cups were installed to take soil water samples in field lysimeters at depths of 55 and 85 cm, and three suction cups were installed in the growth chamber lysimeters at depths of 20, 40 and 60 cm. To permit viewing of the roots during treatments, a clear acrylic plastic tube called a minirhizotron was positioned in nine of the growth chamber lysimeters. The actual position of the water table was determined by observing the water level in a plastic tube installed in all lysimeters. To determine the proper time of irrigation, a neutron probe was installed in all field lysimeters.

Measurements of crop growth parameters such as canopy height, leaf area, and shoot dry matter, and qualitative measurements of roots, plant uptakes, and grain yield were made for all flooding treatments. To determine the nitrate concentration in soil solution, soil water samples were taken during and after flooding treatments. At the end of the growth chamber experiment, nine of the lysimeters were cut, and the soil was washed before determining the quantitative response of flooding on root growth.

CONCLUSIONS

This study resulted in the following conclusions:

1. The two water table depth treatments resulted in different growth and yield values, even at the same SEW_{30} values. Thus, the SEW_{30} concept cannot be used satisfactorily to predict corn yields.
2. Models were developed to predict dry matter yield and grain yield as functions of water table depth.
3. At harvest, a comparison of the percentages lost of dry matter in growth chamber lysimeters and in field lysimeters showed identical effects of flooding treatments. Therefore, the dry matter loss caused by excessive water condition was significantly greater in comparison to other factors such as nutrient-deficiency.
4. All plant measurements showed the effect of wet stress. But leaf area was the most sensitive to excessive soil water conditons and the best indicator for shoot dry-matter yield prediction. Consequently, leaf area may be a good indicator of drainage requirements.
5. Increases in shoot dry matter and in yield caused by maintaining water 15 cm below the soil surface suggest that similar studies need to be conducted to develop practical methods of improving yield under poorly drained conditions, for example, methods incorporating the subirrigation concept.
6. Nitrate loss through drainage was significantly greater for surface flooding than for water table at 15 cm below the soil surface.

7. Nutrient uptake decreased with increased duration of flooding, this relation was not true for water table at 15 cm below the soil surface.

8. Fiber optics can be used for qualitative observation of roots. To obtain a representative sample, a large area should be examined, and more research should be conducted to find a suitable method for installing the observation tube.

9. The quantitative measurement of roots showed that water table at 15 cm below the soil surface, in comparison with surface flooding, resulted in 160, 183, 291, and 275 percent increases in root-area at 90, 180, 270, and 360 cm-days of the SEW_{30} values, respectively.

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APPENDIX A: DATA ON CORN RESPONSE TO HIGH WATER TABLE COLLECTED IN GROWTH CHAMBER LYSIMETERS

Table 1. Effect of SEW_{30} on dry matter weight of corn using two stress levels (surface flooding and water table at 15 cm below the soil surface) in growth chamber lysimeter

Stress level/ DOF[a]	SEW_{30} values (cm-days)	Dry matter per plant (gm) N S T L Rep.1	Rep.2	AGRONOMY Rep.1	Rep.2	Average dry matter weight
		(gm)	(gm)	(gm)	(gm)	(gm)
Surface flooding						
3	90	34.44	31.29	35.32	29.11	32.54 c*
6	180	22.06	21.92	21.93	23.42	22.33 d
9	270	14.44	14.04	14.13	13.87	14.12 e
12	360	7.42	9.62	13.75	10.58	10.34 e
Water table at 15 cm below the soil surface						
6	90	41.17	38.71	40.57	46.60	41.76 a
12	180	40.43	35.86	35.91	36.43	37.16 b
18	270	33.98	37.35	40.70	34.39	36.60 b
24	360	33.06	35.92	34.78	41.74	36.37 b
Control	Opt.	58.21	53.48	51.15	57.05	54.97

[a]Means with the same letter are not significantly different at the 95 percent confidence interval
*Days of flooding

Table 2. Percent loss of dry matter for various water table treatments in comparison to the control treatment in growth chamber lysimeter

Stress level/ DOF[a]	SEW_{30} values (cm-days)	Percent loss of dry matter weight NSTL Rep.1	Rep.2	AGRONOMY Rep.1	Rep.2	Average % loss of dry matter weight
Surface flooding						
3	90	40.83	41.49	30.95	48.97	40.80
6	180	62.10	59.01	57.13	58.95	59.38
9	270	75.19	73.75	72.38	75.69	74.31
12	360	87.25	82.01	73.12	81.45	81.19
Water table at 15 cm below the soil surface						
6	90	29.27	27.62	20.68	18.32	24.03
12	180	30.54	32.95	29.79	36.14	32.40
18	270	41.63	30.16	20.43	39.72	33.42
24	360	43.21	32.83	32.00	26.84	33.84

[a]Days of flooding

Table 3. Average leaf area measurement per plant of corn under different water table treatments in growth chamber lysimeter

Stress level/ DOF[a]	SEW_{30} values (cm-days)	Average leaf area N S T L Rep 1	Rep 2	AGRONOMY Rep 1	Rep 2	Average leaf area of four reps.
		(cm^2)	(cm^2)	(cm^2)	(cm^2)	(cm^2)
Surface flooding						
3	90	4607.67	4691.45	4174.40	4824.07	4574.40 b*
6	180	3646.32	3490.46	3397.73	3673.61	3552.03 c
9	270	2959.68	2622.27	2319.53	2494.07	2598.88 d
12	360	1719.19	2042.87	2296.252	124.42	2045.68 e
Water table at 15 cm below the soil surface						
6	90	5157.675	109.02	5191.035	314.50	5193.05 a
12	180	4696.284	391.33	4568.034	803.95	4614.89 b
18	270	4279.67	4202.46	4442.00	4594.74	4379.71 b
24	360	4331.79	4501.12	4154.67	4621.63	4402.31 b
Control	Opt.	5529.83	5750.45	5631.83	5782.04	5673.54

*Means with the same letter are not significantly different at 95 percent confidence interval

[a]Days of flooding

Table 4. Average canopy height as function of time and SEW_{30} values in growth chamber lysimeter

Stress level/ DOF[a]	SEW_{30} values (cm-days)	Canopy height in cm for days after planting 26	29	32	35	38	44	53
Surface flooding								
3	90	55.22	64.20	71.12	85.66	96.06	132.411	78.38
6	180	56.68	65.78	70.67	80.16	81.64	110.41	163.74
9	270	53.76	62.07	67.77	69.65	70.97	86.76	138.50
12	360	54.15	62.50	67.13	69.51	70.50	81.34	25.63
Water table at 15 cm below the soil surface								
6	90	54.47	68.27	83.10	95.19	111.88	142.29	186.38
12	180	56.21	71.57	84.66	103.70	116.72	139.97	171.07
18	270	53.39	66.03	81.01	96.18	108.81	131.54	162.52
24	360	52.58	62.54	77.72	94.20	107.21	135.66	163.53
Cont.	Opt.	55.45	74.20	89.89	106.02	120.94	145.17	188.96

[a]Days of flooding

Table 5. Effect of water table treatments on the canopy height measured on the day of harvesting in growth chamber lysimeter

Stress level/ DOF[a]	SEW_{30} values (cm-days)	Average canopy height NSTL Rep 1	NSTL Rep 2	AGRONOMY Rep 1	AGRONOMY Rep 2	Overall mean
		(cm)	(cm)	(cm)	(cm)	(cm)
Surface flooding						
3	90	172.00	181.75	185.37	174.38	178.38 ab*
6	180	159.75	149.37	164.35	181.23	163.74 c
9	270	141.37	129.88	140.00	142.74	138.50 d
12	360	118.75	122.65	128.75	132.38	125.63 e
Water table at 15 cm below the soil surface						
6	90	183.25	174.25	197.25	190.75	186.38 a
12	180	168.13	152.51	93.00	170.63	171.07 cb
18	270	161.00	148.63	168.75	171.75	162.52 c
24	360	155.25	169.38	157.75	171.38	163.53 c
Control	Opt.	179.25	179.32	198.50	193.45	188.96

*Means with the same letter are not significantly different at the 95 percent confidence level

[a]Days of flooding

Table 6. Effect of water table treatments on the stem height measured on the day of harvesting in growth chamber lysimeter

Stress level/ DOF[a]	SEW_{30} values (cm-days)	Average stem height NSTL Rep 1	NSTL Rep 2	AGRONOMY Rep 1	AGRONOMY Rep 2	Average stem height of 4 runs
		(cm)	(cm)	(cm)	(cm)	(cm)
Surface flooding						
3	90	4.75	76.13	77.95	78.12	74.24 ab*
6	180	61.63	54.75	65.33	86.20	66.98 c
9	270	50.75	46.38	53.83	60.75	52.93 ed
12	360	44.37	46.00	50.30	55.88	48.89 e
Water table at 15 cm below the soil surface						
6	90	71.50	69.38	90.82	96.85	82.14 a
12	180	62.75	53.75	89.12	79.38	71.25 cb
18	270	60.25	49.75	71.95	71.75	63.43 cd
24	360	58.50	64.138	58.65	67.88	62.29 c
Control	Opt.	68.75	76.50	92.97	100.00	84.56

*Means with the same letter are not significantly different at the 95 % confidence interval

[a]Days of flooding

Table 7. Average stem height as a function of time and SEW30 values in growth chamber lysimeter

Stress level/ DOF[a]	SEW30 values (cm-days)	Stem height in cm for different days after planting 26	29	32	35	38	44	53
Surface flooding								
3	90	13.40	16.09	16.79	19.97	25.62	42.95	69.90
6	180	13.73	15.94	17.85	18.96	20.38	35.71	66.98
9	270	12.71	15.64	17.19	18.21	18.39	27.97	52.93
12	360	12.64	16.05	16.95	17.71	18.52	27.75	48.89
Water table at 15 cm below the soil surface								
6	90	12.27	14.92	20.30	24.78	28.29	45.19	82.14
12	180	13.77	16.60	21.35	23.88	30.97	43.25	71.25
18	270	13.24	15.20	19.05	23.87	27.52	42.53	62.29
24	360	12.36	15.20	19.05	23.87	27.52	42.53	62.29
Cont.	Opt.	13.19	18.19	22.02	26.55	31.61	51.53	84.56

[a]Days of flooding

APPENDIX B: DATA ON CORN RESPONSE TO HIGH WTER TABLE COLLECTED IN FIELD LYSIMETERS

Table 1. Average grain yield per plant of corn as function of SEW_{30} and flooding treatment in field lysimeters

Stress Level DOF[a]	SEW_{30} Values (cm-days)	Grain weight per plant Years 1989 Rep. 1	1990 Rep. 1	1990 Rep.2	Overall Average
		(gm)	(gm)	(gm)	(gm)
Surface flooding					
3	90	156.61	158.96	126.74	147.43
6	180	113.86	132.86	124.98	123.90
9	270	108.38	110.52	106.18	108.36
12	360	73.29	84.79	106.65	88.24
Water table at 15 cm below the soil surface					
6	90	151.13	164.04	158.83	158.00
12	180	142.83	132.04	163.82	146.32
18	270	129.40	130.07	134.46	131.31
24	360	124.71	138.45	152.61	138.59
Control	Opt.	213.46	204.61	187.11	201.73

[a]Days of flooding

Table 2. Percent grain yield as a function of SEW_{30} and water table treatments in field lysimeters

Stress Level DOF[a]	SEW_{30} Values (cm-days)	Percent Loss of Grain Yield Years 1989 Rep. 1	1990 Rep. 1	1990 Rep.2	Average % loss of grain yield
Surface flooding					
3	90	26.63	22.31	32.27	27.07
6	180	46.66	35.07	33.20	38.31
9	270	49.23	45.99	43.25	46.15
12	360	65.67	58.56	43.00	55.74
Water table at 15 cm below the soil surface					
6	90	29.20	19.83	15.12	21.38
12	180	33.09	35.47	12.45	27.00
18	270	39.38	36.43	28.14	34.65
24	360	41.58	32.33	18.44	30.78

[a]Days of flooding

Table 3. Shoot dry matter as function of SEW_{30} and water table treatments in field lysimeters

Stress Level DOF[a]	SEW_{30} Values (cm-days)	Dry Matter Per Plant Years 1989 Rep. 1	1990 Rep. 1	Rep.2	Average
		(gm)	(gm)	(gm)	(gm)
Surface flooding					
3	90	80.42	88.21	90.24	86.29
6	180	70.63	77.43	68.92	72.33
9	270	60.75	65.52	71.08	65.78
12	360	57.42	52.08	57.29	55.60
Water table at 15 cm below the soil surface					
6	90	82.56	104.36	94.43	93.78
12	180	76.33	89.32	93.62	86.42
18	270	91.55	71.44	86.02	83.00
24	360	67.5	100	108.73	92.08
Control	Opt.	94.08	136.78	112.67	114.51

[a]Days of flooding

Table 4. Percent shoot dry matter loss as a function of SEW_{30} and water table treatments in field lysimeters

Stress Level DOF[a]	SEW_{30} Values (cm-days)	Dry Matter Per Plant Years 1989 Rep. 1	1990 Rep. 1	1990 Rep.2	Average
		(gm)	(gm)	(gm)	(gm)
Surface flooding					
3	90	14.52	35.51	19.91	23.31
6	180	24.93	43.39	38.83	35.72
9	270	35.43	52.10	36.91	41.48
12	360	38.97	61.92	49.15	50.01
Water table at 15 cm below the soil surface					
6	90	12.24	23.70	16.19	17.38
12	180	18.87	34.70	16.91	17.38
18	270	2.69	47.77	23.65	24.70
24	360	28.25	26.89	3.50	19.55

[a]Days of flooding

Table 5. Average canopy height response as a function of time and SEW_{30} values in field lysimeters

Stress Level DOF[a]	SEW_{30} Values (cm-days)	Canopy height in cm for different days after planting 36	39	42	46	49	55	61
Surface flooding								
3	90	79.78	91.43	100.09	109.97	126.50	165.98	183.98
6	180	86.70	104.18	106.96	119.67	137.72	159.43	173.90
9	270	87.04	101.68	111.03	119.17	126.48	148.81	159.48
12	360	84.91	100.46	108.85	115.14	116.21	129.65	134.88
Water table at 15 cm below the soil surface								
6	90	88.37	103.58	115.31	125.53	144.53	176.58	187.57
12	180	84.71	101.34	117.38	124.87	146.01	176.53	185.05
18	270	88.93	107.47	120.44	131.23	148.40	171.98	184.65
24	360	85.72	90.32	108.06	115.64	127.69	160.30	172.96
Control	Opt.	87.02	113.23	129.57	143.66	166.91	201.46	211.87

[a]Days of flooding

Table 6. Effect of water table treatment on canopy height measured on the last day of treatment (24 days of surface flooding)

Stress Overall Levels DOF[a]	SEW_{30} values (cm-days)	Average canopy height 1989 Rep. 1	Rep. 2	1990 Rep. 1	Rep. 2	canopy height
		(cm)	(cm)	(cm)	(cm)	
Surface flooding						
3	90	182.57	186.84	177.08	189.42	183.98
6	180	173.13	181.05	178.25	163.33	173.94
9	270	153.92	149.05	169.25	165.67	159.47
12	360	123.14	145.39	135.08	135.92	134.88
Water table at 15 cm below the soil surface						
6	90	169.46	187.15	205.33	188.33	187.58
12	180	147.22	172.83	203.25	216.92	185.06
18	270	181.05	194.46	171.25	191.83	184.65
24	360	160.63	153.62	196.75	180.83	172.96
Control	Opt.	213.06	210.01	212.5	211.92	211.87

[a]Days of flooding

APPENDIX C: NITRATE-NITROGEN CONCENTRATION DATA

Table 1. Nitrate-nitrogen concentration in soil water solution as a function of depth and water table treatment in growth chamber lysimeters

Treatment Depth	DOF[a]	Days after Planting 29	32	35	38	42	48
Surface flooding							
20 cm	3	14.93	6.52	22.66	29.40	14.39	19.10
	6	12.36	11.35	8.32	12.54	10.01	7.93
	9	17.19	14.83	13.91	4.35	11.29	20.53
	12	14.92	23.95	16.58	6.69	2.74	16.93
Water table at 15 cm below the soil surface							
	6	13.19	11.27	2.77	3.86	4.24	0.65
	12	9.31	7.46	1.25	0.03	0.00	0.80
	18	14.78	12.23	5.10	0.62	0.02	0.01
	24	13.00	11.23	8.12	6.61	1.55	1.32
	Control	33.22	32.73	30.170	10.52	4.54	0.58
Surface flooding							
40 cm	3	3.31	0.01	3.09	3.50	1.88	0.38
	6	0.02	0.01	0.02	2.19	1.99	0.62
	9	3.88	2.04	0.75	0.75	0.77	1.76
	12	15.05	14.75	20.17	8.28	4.01	2.09
Water table at 15 cm below the soil surface							
	6	0.38	0.06	0.02	0.00	0.00	0.03
	12	1.13	0.02	0.03	0.03	0.02	0.00
	18	0.93	0.03	0.02	0.91	0.03	0.25
	24	1.44	1.07	0.19	0.01	0.00	0.00
	Control	0.00	0.00	0.01	0.01	0.00	0.14
Surface flooding							
60 cm	3	0.02	3.92	10.08	15.57	12.49	3.11
	6	0.02	0.00	0.02	2.25	0.66	0.00
	9	0.02	0.37	1.08	1.07	1.03	0.07
	12	0.27	1.04	0.17	2.10	0.02	0.04
Water table at 15 cm below the soil surface							
	6	0.02	0.02	0.03	0.00	0.00	0.00
	12	14.75	4.88	1.18	0.03	0.02	2.13
	18	0.01	0.03	0.01	2.13	0.03	0.02
	24	0.05	0.00	0.01	0.04	0.00	0.00
	Control	0.01	0.00	0.02	0.00	0.00	0.01

[a]Days of flooding

Table 2. Average nitrate-nitrogen obtained from drained water of growth chamber lysimetres

Treatment	DOF[a]	NSTL Rep 1	NSTL Rep 2	AGRONOMY Rep 1	AGRONOMY Rep 2	Overall Average
		Average Nitrate Per Plant				
		(mg)	(mg)	(mg)	(mg)	(mg)
Surface flooding						
	3	464.78	482.33	352.66	425.24	431.25
	6	454.08	401.10	216.77	192.82	316.19
	9	163.69	34.56	22.28	137.95	89.62
	12	109.55	28.18	132.99	66.94	84.41
Water table at 15 cm below the soil surface						
	6	0.42	0.03	0.39	0.04	0.22
	12	0.16	0.06	0.05	0.13	0.10
	18	0.15	0.10	0.10	0.78	0.28
	24	0.14	0.08	0.04	0.10	0.09

[a]Days of flooding

Table 3. Nitrogen uptake under high water table conditions in growth chamber lysimeters

Overall Treatment	DOF[a]	Average Nitrogen Uptake Per Plant NSTL Rep. 1	NSTL Rep. 2	AGRONOMY Rep. 1	AGRONOMY Rep. 2	Average
		(mg)	(mg)	(mg)	(mg)	(mg)
Surface flooding						
	3	440.83	657.09	717.00	480.31	573.81
	6	348.55	412.10	438.60	480.11	419.84
	9	268.58	293.44	337.71	345.36	311.27
	12	195.89	284.75	291.50	282.49	263.66
Water table at 15 cm below the soil surface						
	6	551.68	661.94	604.49	666.38	621.12
	12	566.02	469.77	588.92	644.81	567.38
	18	458.73	612.54	577.94	605.26	563.62
	24	456.23	592.68	473.01	509.23	507.79
Control		617.03	721.98	705.87	678.90	680.94

[a]Days of flooding

Table 4. Effect of surface flooding and water table at 15 cm below the soil surface on phosphorous uptake per plant in growth chamber study

		Average Phosphorous Per Plant				
		NSTL		AGRONOMY		
Overall Treatment	DOF[a]	Rep. 1	Rep. 2	Rep. 1	Rep. 2	Average
		(mg)	(mg)	(mg)	(mg)	(mg)
Surface flooding						
	3	37.88	87.61	38.85	148.46	78.20
	6	48.53	67.95	32.89	65.58	53.74
	9	34.66	49.14	14.13	37.45	33.84
	12	17.07	32.71	17.88	33.86	25.38
Water table at 15 cm below the soil surface						
	6	53.52	69.68	48.68	130.48	75.59
	12	28.30	68.13	82.59	80.15	64.79
	18	33.98	85.91	28.49	75.66	56.01
	24	13.22	75.43	52.17	91.83	58.16
Control		39.58	165.79	27.62	165.45	99.61

[a]Days of flooding

Table 5. Effect of surface flooding and water table at 15 cm below the soil surface on potassium uptake per plant in growth chamber study

	Average Potassium Uptake Per Plant				
	NSTL		AGRONOMY		
Overall Treatment DOF[a]	Rep1	Rep2	Rep1	Rep2	Average
	(mg)	(mg)	(mg)	(mg)	(mg)
Surface flooding					
3	665.55	441.19	886.53	410.45	600.93
6	616.58	611.57	517.00	653.42	599.64
9	640.05	431.03	393.52	337.04	450.41
12	348.37	295.33	365.06	317.40	331.54
Water table at 15 cm below the soil surface					
6	1192.90	750.97	986.87	904.04	958.70
12	792.43	584.52	649.97	658.38	671.58
18	787.49	511.70	540.29	529.61	592.27
24	665.33	463.37	446.92	534.27	527.47
Control	752.36	802.20	774.92	718.83	762.08

[a]Days of flooding

Table 6. Average nitrate residual as a response of water table treatments in growth chamber lysimeters

Treatment	DOF[a]	0-15cm	15-30cm	30-45cm	Average Lysimeter	Nitrates/ ha
		(mg)	(mg)	(mg)	(mg)	(kg)
Surface flooding						
	3	255.51	259.17	234.83	749.51	38.73
	6	200.07	223.81	473.82	897.7	46.39
	9	418.46	473.82	267.15	1159.43	59.92
	12	1289.48	508	229.45	2026.93	104.75
Water table at 15 cm below the soil surface						
	6	247.32	228.55	233.46	709.33	36.66
	12	246.96	282.7	218.74	748.4	38.68
	18	379.13	456.99	280.26	1116.38	57.69
	24	184.19	229.45	233.22	646.86	33.43
Control		149.04	229.45	233.22	611.71	31.61

[a]Days of flooding

Table 7. Nitrate-nitrogen concentration in soil water solution as function of water table treatments in field lysimeters

Treatment		Days After Planting								
DOF[a]	Depth	39	42	45	48	51	57	63	69	75
Surface flooding										
3	60	74.47	83.56	75.25	65.81	75.25	81.56	37.69	3.50	0.03
6	60	85.39	72.46	50.30	50.30	40.45	28.56	7.23	0.03	0.03
9	60	77.26	62.84	30.96	15.27	30.96	15.27	6.95	0.01	0.03
12	60	76.26	60.58	17.53	5.83	17.53	0.52	0.1	0.03	0.03
Water table at 15 cm below the soil surface										
6	60	58.70	59.96	51.75	51.75	40.38	26.98	10.77	0.01	0.03
12	60	66.25	46.78	61.76	50.24	61.76	43.37	0.02	0.02	0.02
18	60	46.81	54.07	23.30	13.48	23.30	3.30	0.02	0.63	1.10
24	60	59.33	47.70	8.86	2.53	8.86	1.16	0.39	0.01	0.89
Control	60	63.86	84.32	172.99	178.95	172.99	119.90	32.37	29.88	8.86
Surface flooding										
3	90	48.43	53.72	54.22	48.12	54.22	43.46	37.69	45.85	23.92
6	90	17.52	31.99	23.24	23.24	20.25	9.41	4.11	0.02	0.02
9	90	61.81	24.87	11.76	7.11	11.76	8.12	5.13	0.62	0.03
12	90	44.28	40.52	15.86	5.24	15.86	2.28	3.9	1.26	0.01
Water table at 15 cm below the soil surface										
6	90	36.23	30.34	23.10	23.1	23.10	28.43	14.10	0.02	6.42
12	90	40.79	40.55	23.56	19.46	23.56	16.27	0.01	6.91	0.03
18	90	16.41	15.22	11.79	8.91	11.79	5.72	6.08	0.01	0.03
24	90	20.15	18.51	16.18	10.02	16.18	3.74	0.53	0.33	0.03
Control	90	16.46	24.89	16.85	20.07	16.85	25.29	5.42	0.06	0.03

[a]Days of flooding

Table 8. Percentage nitrogen concentration and uptake per plant as a function of days after planting (DAP) and water table treatments in field lysimeters

Treatment DOF[a]	Before TREATMENT (35th DAP) (nitrogen concentration)	After TREATMENT 60th DAP	Harvesting 110th DAP)	Before TREATMENT (35th DAP (mg)	After TREATMENT 60th DAP (mg)	Harvesting 110th DAP (mg)
Surface flooding						
3	3.80	1.53	0.55	226.10	1087.16	586.58
6	3.62	1.07	0.54	249.44	590.61	380.94
9	3.48	1.09	0.47	257.17	579.74	321.57
12	3.33	0.95	0.60	245.05	496.66	298.42
Water table at 15 cm below the soil surface						
6	3.52	1.47	0.43	253.44	1367.98	617.99
12	3.74	1.20	0.42	298.45	1307.94	379.71
18	3.24	1.34	0.46	256.61	825.33	332.12
24	3.36	1.62	0.54	260.01	983.92	417.70
Control	3.28	1.16	0.60	249.56	1759.41	681.54

[a]Days of flooding

Table 9. Percentage phosphorous concentration and uptake per plant as a function of water table treatments in field lysimeters

Treatment	DOF[a]	Average P Concentration % Rep 1	Rep 2	Average P Uptakes/plant Rep 1	Rep 2	Overall Average P Uptake
				(mg)	(mg)	
Surface flooding						
	3	0.27	0.198	238.17	178.68	208.42
	6	0.15	0.16	116.15	110.27	113.21
	9	0.11	0.12	72.07	85.30	78.68
	12	0.094	0.08	48.96	45.83	47.39
Water table at 15 cm below the soil surface						
	6	0.169	0.16	176.37	151.09	163.73
	12	0.14	0.15	125.05	140.43	132.74
	18	0.154	0.11	110.02	94.62	102.32
	24	0.1	0.111	100.00	120.69	110.35
Control		0.119	0.1	0.11	113.59	124.38

[a]Days of flooding

Table 10. Potassium concentration and uptake per plant as a function of water table treatments in field lysimeters

Treatment	DOF[a]	Average K Conc. % Rep. 1	Rep. 2	Average K uptake/plant Rep. 1	Rep. 2	Overall Average K. Uptake
Surface flooding						
	3	0.99	0.87	873.28	785.09	829.18
	6	0.81	0.81	627.18	558.25	592.72
	9	0.70	0.75	458.64	533.10	495.87
	12	0.74	0.72	385.39	412.49	398.94
Water table at 15 cm below the soil surface						
	6	1.07	1.01	1116.65	953.74	1035.20
	12	1.08	0.96	964.66	898.75	931.70
	18	0.95	0.96	678.68	825.79	752.24
	24	0.8	0.71	800.00	771.98	785.99
Control		0.97	0.71	1326.77	799.96	1063.36

[a]Days of flooding

Table 11. Average nitrate residual as a function of water table treatments in field lysimeter

Treatment	DOF[a]	0-15cm	15-30cm	30-60cm	N(mg/lys)	N(kg/ha)
Surface flooding						
	3	990.86	1596.5	4159.14	6746.5	32.75
	6	2033.22	2270.12	6188.24	10491.58	50.93
	9	2066.18	2756.28	6039.92	10862.38	52.73
	12	3497.88	4801.861	10681.11	18980.84	92.14
Water table at 15 cm below the surface						
	6	2694.48	1707.74	3199.18	7601.4	36.9
	12	1854	1952.88	3990.22	7797.1	37.85
	18	2640.92	2770.7	5141.76	10553.38	51.23
	24	2628.56	1971.42	4179.74	8779.72	42.62
Control		2278.36	1989.96	4035.54	8303.86	40.31

[a]Days of flooding