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STRESS DAY INDEX MODELS TO PREDICT CORN AND SOYBEAN YIELD RESPONSE TO WATER TABLE MANAGEMENT

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ABSTRACT. Drainage and related agricultural water table management systems are being designed in humid regions of the United States using the water management simulation model, DRAINMOD. Since excessive and deficient soil-water conditions are stressful to most crops, crop yield is a useful measure of the effectiveness of the water management system design. Stress day index (SDI) models are presented which can be used to predict corn and soybean yield response to excessive and deficient soil-water conditions. The relative yield - SDI models developed herein and SDI models reported in the literature were tested using a comprehensive data base developed from corn and soybean yield studies conducted in eastern North Carolina over the past 35 years.

RESUME ET CONCLUSIONS. Connaissances acquises: *Aux Etats-Unis, les systèmes de drainage des zones humides ainsi que les techniques de gestion du niveau de nappe qui y sont liées, ont été élaborés en utilisant le modèle de gestion DRAINMOD. Le rendement de la plupart des cultures est influencé par l'excès ou le déficit d'eau dans le sol. Le rendement d'une culture est donc une mesure utile pour apprécier l'efficacité d'un système de gestion d'eau. Des indices de stress hydriques (SDI) ont été développés pour quantifier la réduction de rendement due aux conditions de stress hydrique existant dans le sol. La méthode des SDI prend en compte d'une part, la mesure du degré (quantité) de stress imposé à la culture, et d'autre part, sa sensibilité au stress qui est fonction de l'espèce cultivée et de son stade de développement.*

Objectifs *- Le but de cette étude était triple. Premièrement, déterminer expérimentalement les facteurs de sensibilité culturale (CS) pour des cultures de maïs et de soja stressées par un excès d'eau dans le sol. Deuxièmement, développer des modèles d'indice de stress hydrique pour prédire le rendement de cultures de maïs et de soja soumises à des niveaux de nappe élevés, en se basant sur les facteurs CS déterminés expérimentalement. Troisièmement, tester à la fois les modèles SDI que nous avons développés pour un stress hydrique dû à un excès d'eau, ainsi que les modèles SDI mentionnés dans la littérature, pour prédire le rendement cultural en cas de stress provoqué par un déficit hydrique. Le rendement prédit (calculé) est comparé au rendement mesuré sur les sites d'expérimentation.*

Modèles d'indice de stress hydrique pour predire la variation de rendement du maïs et du soja en fonction de la gestion du niveau de nappe.

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***Protocole expérimental** - Les facteurs de sensibilité culturale ont été déterminés pour des plantes soumises à un excès d'eau durant cinq stades de leur développement physiologique. Les expérimentations ont été conduites en cases lysimétriques pour les cinq stades de développement physiologique déterminés à partir de la bibliographie. Les périodes de stress ont été déclenchées en remontant le niveau de la nappe à proximité de la surface du sol, une fois pendant dix jours consécutifs pour le maïs et une fois pendant sept jours consécutifs pour le soja, et ce pour chacun des cinq stades de développement retenus. Le maïs était plus sensible àl'excès d'eau juste avant le stade de formation des grains; le soja, durant les stades de développement et de remplissage de la gousse.*

Des modèles ont été proposés pour prédire le rendement relatif de cultures de maïs et de soja soumises à un niveau de nappe élevé. Ces modèles sont basés sur des analyses de régression faites à partir de données expérimentales obtenues dans l'état de l'Ohio. La durée des observations était de treize ans pour le maïs et de six ans pour le soja. Ces modèles utilisent l'indice de stress hydrique SDI, fonction des facteurs SEW_{30} et CS. Le facteur SEW_{30} représente un critère du stress engendré par un niveau de nappe élevé. Le facteur CS est déterminé expérimentalement. Le modèle "maïs" a été validé avec des données provenant d'Inde et de Caroline du Nord; en utilisant la totalité des données, il expliquait 69 pourcent de la variance du rendement relatif. Le modèle "soja" expliquait 66 pourcent de cette variance pour les six années de données obtenues dans l'Ohio.

Les modèles "rendement-SDI" que nous avons développés, et les modèles SDI de la littérature, ont été validés en utilisant une importante base de données issue des recherches menées sur le rendement des cultures de maïs et de soja dans l'est de la Caroline du Nord. Les expérimentations de terrain ont fourni l'équivalent de 94 observations pour le rendement du maïs, et de 128 observations pour le rendement du soja. Les stress hydriques journaliers, pour différentes conditions climatiques, ont été simulés avec DRAINMOD. Préalablement à la simulation des rendements, les données d'entrée du modèle ont été vérifiées en comparant les niveaux de nappe simulés et observés pour 12 combinaisons sites-années. La réduction de rendement liée à un stress hydrique (excès ou déficit), ainsi que le retard des semis, ont été simulés.

***Résultats** - Douze modèles SDI ont été comparés et validés pour le maïs. Tous les modèles testés ont fourni un relativement bon ajustement avec les 94 données relatives au rendement du maïs: l'erreur moyenne variait de -0.1 pour-cent à -6.1 pour-cent. L'erreur moyenne augmentait lorsque l'on introduisait un facteur de pondération pour les périodes de déficit hydrique marqué. La corrélation calculée par rapport à la droite de pente 1:1, entre les rendements calculés et observés sur l'ensemble des données, variait de 66.6 à 79.5 pour-cent. Ceci laisse supposer que les méthodes de simulation étaient sensibles à la variation inter-annuelle du rendement, liée à la variabilité du stress hydrique.*

Le modèle "rendement soja-SDI" a fourni de relativement bonnes prédictions à long terme pour le calcul du rendement moyen: l'erreur moyenne était de -0.4 pour-cent. Cependant, le modèle n'était pas aussi fiable pour prédire la variation de rendement d'une année sur l'autre. La corrélation entre rendements simulés et observés, calculée par rapport àla droite de pente 1:1 , n'était que de 47.9 pour-cent. Les résultats de cette étude ont montré que des méthodes simples comme celles des SDI utilisant DRAINMOD pour simuler les conditions hydriques du sol, peuvent fournir des estimations du rendement moyen, sur de longues périodes, pour des cultures de maïs et de soja soumises à des niveaux de nappe élevés.

INTRODUCTION

Rainfall is extremely variable during the growing season in the southeastern U.S. It seldom occurs in an amount and distribution necessary to achieve high yields more often than about one year in ten. In other years, soil-water, either too much and/or too little, is usually the single most limiting factor for high yields (Sopher, 1969).

Yield reductions often develop from stresses caused by excessive soil-water conditions on poorly drained soils. The yield reductions may result either (1) from the inability to plant and tend the crop at the right time due to poor trafficability or (2) from direct damage to the crop due to a lack of oxygen (anaerobiosis); biochemical toxicity; and/or nutrient deficiencies; resulting from an elevated water table or excessive soil-water condition. Although annual rainfall exceeds evapotranspiration on the average, droughts ranging from a few days up to several weeks occur in many years between June and September. While excessive soil-water is a major concern, substantial yield reductions resulting from deficient soil-water conditions occur frequently, even on poorly drained soils.

The primary purposes of agricultural water management systems are to increase production efficiency and yield reliability by improving the soil-water environment. Crop yield is a practical measure of crop response to water stresses for the purpose of optimizing the water management system design. The stress-day-index (SDI) approach (Hiler, 1969) was developed to quantify the cumulative effect of stresses imposed on a crop throughout the growing season.

Evans et al. (1990) reported crop susceptibility factors for corn and soybean stressed by excessive soil-water conditions. Using these crop susceptibility factors and field data from Ohio, Evans et al. (1991) developed yield - SDI relationships to estimate corn and soybean yield response to excessive soil water conditions. Evans and Skaggs (1992) tested these yield - SDI relationships along with other SDI models reported in the literature against corn and soybean yields observed in field experiments conducted in eastern North Carolina. The purpose of this paper is to summarize the Stress Day Index relationships developed and tested in North Carolina.

STRESS DAY INDEX APPROACH

The general form of the SDI concept described by Hiler (1969) may be expressed

$$SDI_X = \sum_{i=1}^{n} SD_i \; CS_i \qquad (1)$$

where n is the number of growth periods (distinct stages of physiological development) and SD and CS are stress day and crop susceptibility factors for period i, respectively. The subscript x has been added herein and when replaced by w, d, or p is used to denote the specific yield reducing condition, either wet, dry or planting delay, respectively.

Stress Day Factor

The stress day factor (SD) is a measure of the intensity and duration of stress. Sieben (1964) related crop response to fluctuating water tables using so-called SEW_{30} values computed from

$$SEW_{30} = \sum_{i=1}^{n} 30 - x_i \qquad (2)$$

where x_i is the water table depth below the soil surface on day i, and n is the number of days in the period being considered. Negative terms inside the summation are neglected such that the summation is a measure of the exceedence of some critical water table depth. Sieben (1964) assumed the critical depth to be 30 cm, so the SEW_{30} value has units of cm-days.

Shaw (1974) related corn yield to deficient soil-water conditions. He defined a stress day factor based on 5-day evapotranspiration (ET) deficient computed as

$$SD_i = WF \times \sum_{j=1}^{5} 1 - ET_{ij} / PET_{ij} \qquad (3)$$

where SD_i was the stress factor for period i, ET_{ij} was the actual evapotranspiration that occurred in period i, on day j, and PET_{ij} was the potential evapotranspiration in period i, on day j. The SD_i was computed for 5-day intervals beginning 40 days prior to silking and ending 44 days after silking for a total of 17 5-day periods. Whenever the stress day factor for two or more consecutive 5-day periods was greater than 4.5, (maximum possible value is 5.0) a severe stress weighting factor (WF in equation 3) of 1.5 was used; otherwise, the WF was 1.0.

Skaggs et al. (1982) developed a relationship to estimate the effect of planting date delay on corn yield. Their relationship was developed from non-irrigated planting date studies presented by Krenzer and Fike (1977). Seymour et al. (1992) conducted similar planting date studies on a field with subirrigation. After combining results of the two studies, Seymour et al. (1992) defined the plant delay stress day factor as the number of days planting was delayed past an "optimum" date for a given location.

Crop Susceptibility Factor

The crop susceptibility factor is a measure of the crop susceptibility to a unit of stress and is a function of crop species and its stage of development. The crop susceptibility factor is determined experimentally by subjecting the crop to a critical level of stress during each discrete physiological growth stage and measuring the yield response. The crop susceptibility factor for each growth stage as defined by Hiler (1969) is computed by

$$CS_i = \frac{X - X_i}{X} \qquad (4)$$

where X_i is the harvested crop yield when subjected to the critical stress at growth stage i and X is the crop yield when no stress is applied. Crop susceptibility factors have been reported for a few crops (Desmond et al., 1985; Evans et al., 1990; Evans, 1991; Hiler and Clark, 1971; Mukhtar et al., 1990; Ravelo et al., 1982; Seymour et al., 1992; Shaw, 1974; Sudar et al., 1979).

Evans et al. (1990) reported crop susceptibility factors determined for corn and soybean plants stressed by excessive soil-water conditions during six physiological growth stages. Experiments were conducted using lysimeters with stress periods induced by raising the water table to the soil surface once for ten consecutive days for corn and for seven consecutive days for soybean. Their results are summarized in Table 1.

Shaw (1974) developed crop susceptibility factors to relate corn yield to deficient soil-water conditions, Table 2. Shaw's values were developed from controlled experiments conducted by Denmead and Shaw (1960); Wilson (1968); Classen and Shaw (1970); and Mallett (1972). For periods other than shown in Table 2, a susceptibility factor of zero (0) is used.

Soybean yield response to dry stress has been reported in several studies (Brown et al., 1985; Hiler et al., 1974; Sepaskhah, 1977; Sionit and Kramer, 1977; Smajstrla and Clark, 1982; Snyder et al., 1982). Evans et al. (1986) compared susceptibility factors determined from these studies and found them to be quite variable. Sudar et al. (1979) estimated soybean CS values for Iowa from the literature. While not specifically stated, the values reported by Sudar were likely developed for indeterminate varieties typically grown in the Midwestern U.S. Evans (1991) combined the results reported by Sudar with other data in the literature to develop CS values to estimate the sensitivity of determinate variety soybean to dry stress. The estimates reported by Evans (1991) and used herein are summarized in Table 3.

CORN Growth Stage#	Development& Stage	Period During Growing Season CS Values Used		
		Start	Stop	CS Factors
	Days After Planting ------ DAP -------			
Establishment	Stage 1	0	29	0.20
Vegetative (rapid growth)	Stage 2	30	49	0.22
Late Vegetative	Stage 3-4	50	69	0.32
Flowering (pollination)	Stage 5-6	70	89	0.19
Yield Formation	Stage 7-8	90	109	0.08
Ripening	Stage 9-10	110	130	0.02+
SOYBEAN	Stage@			
Establishment	V0-V4	0	24	0.19
Vegetative	V5-V13	25	54	0.13
Flowering	V14-V17/R1-R2	55	74	0.19
Pod Development	R3-R4	75	94	0.26
Pod Filling	R5	95	109	0.25
Ripening				
(Pods w/full size beans)	R6	110	124	0.08
(Pods yellowing)	R7	125	134	0.01
(Pods brown)	R8	135	145	0.00

After Doorenbos and Kassam (1979).
& Refers to stage of corn development as described by Hanway (1963).
@ Refers to stage of soybean development described by Fehr et al. (1971).
+ Value estimated from graph of corn CS values versus DAP.
^ Values estimated from graph of soybean CS values versus DAP.

Table 1. Growth stage and CS values used to develop SDI relationships for excessive soil-water stresses (eq. 9 for corn, eq. 12 for soybean). (After Evans et al., 1990)

	Growing period*			
Period#	Relative to planting		Relative to silking	CS
	---------------- Days -------------			
	0 to 39			0.0
-8	40 to 44		-40 to -36	0.5
-7	45 to 49		-35 to -31	0.5
-6	50 to 54		-30 to -26	1.0
-5	55 to 59		-25 to -21	1.0
-4	60 to 64		-20 to -16	1.0
-3	65 to 69		-15 to -11	1.0
-2	70 to 74		-10 to -6	1.75
-1	75 to 79		-5 to -1	2.0
0	80		50% silked	
+1	80 to 84		0 to +4	2.0
+2	85 to 89		+5 to +9	1.3
+3	90 to 94		+10 to +14	1.3
+4	95 to 99		+15 to +19	1.3
+5	100 to 104		+20 to +24	1.3
+6	105 to 109		+25 to +29	1.3
+7	110 to 114		+30 to +34	1.2
+8	115 to 119		+35 to +39	1.0
+9	120 to 124		+40 to +44	0.5
	125 to black layer		+45 to maturity	0.0

* Days relative to planting are based on the typical medium maturity variety (1500 GDD (growing degree days ^{o}F) to silking or comparative relative maturity, CRM, group 114 to 116) grown under eastern N.C. conditions and planted on April 10. Early maturity varieties (1350 to 1500 GDD to silking, CRM 100 to 114) will silk 1 to 5 days sooner than shown. Late maturity varieties (1500 to 1700 GDD to silking, CRM 116-130) will silk 1 to 5 days later than shown. On average, the number of calendar days to silking decreases as planting is delayed past April 10.
# Value represents 5-day periods relative to silking as reported by Shaw.

Table 2. Crop susceptibility factors used in eq. 10 to evaluate deficient soil-water conditions on corn yield. (After Shaw, 1974).

DEVELOPMENT OF STRESS DAY INDEX MODELS

Once the crop susceptibility factors are known, the relationship between crop yield and SDI can be determined for a given type of stress (excess, deficient, plant delay) from experimental data using regression analysis to relate yield to the actual soil-water conditions (Stress Day Factor). These experimental data should be different from those used to determine the CS factors. The generalized yield SDI relationship determined from simple linear regression is given by:

$$Y_i = Y_p - a\,SD_i \qquad (5)$$

Stage of Development	Duration of Period	Crop Susceptibility
	DAP	
Plant to V5	0 - 32	0.01
V5 - V15	32-74	0.03
V15(R1) - V17	74 - 81	0.05
R2 (early)	81 - 91	0.10
R2 (late)	91 - 102	0.15
R3 - R4	102 - 115	0.20
R5	115 - 133	0.10
R6 (early)	133 - 146	0.05
R6 (late)	146 - 160	0.02
R7	160 - 170	0
R8	170	0

* Values shown are for Group VI maturity. Plant to R1 occurs about 5-10 days sooner for Group V varieties and 5-10 days later for Group VII varieties. The period R3 to R7 is typically 55 to 60 days, regardless of planting date. In North Carolina, plant delays reduce the length of the time from planting to R3 by about 1 day for each 2 days delay in planting up to June 15. From June 15 to July 5, the ratio is about 1:3, after July 5, the ratio is about 1:4.

Table 3. Crop susceptibility values used in eq. 13 to relate soybean yield (determinate varieties) to deficient soil water stresses. (After Sudar et al., 1979; Evans, 1991).

where Y_i is the actual yield (kg/ha) observed in year i, Y_p is the potential or base maximum yield that would occur in the absence of any soil-water related stress, a is the yield reduction per unit of SDI (slope of regression line). The SDI_i is computed from equation 1 using the appropriate CS values from Tables 1, 2 or 3 and equation 2 or 3 to compute the SD factor. When expressed in terms of actual yield, Y_i, Y_p, and a are site dependent, influenced by a variety of factors including soil, climate, fertility, crop variety, etc. The influence of these factors can be minimized by normalizing equation 5 to

$$RY_i = Y_i/Y_p = 1 - b\ SD_i \tag{6}$$

where RY_i is the relative yield, which when multiplied by 100, is expressed as a percent of potential yield, Y_p; and b is the RY reduction per unit of SDI. Equation 6 is more universal than equation 5 because the Y_p accounts for the influence of soil, climate, fertility, and crop variety.

Evans et al (1991) developed yield - SDI models to relate corn and soybean yields to excessive soil-water conditions. The relative yield models were based on SDI relationships using SEW_{30} (0.3-m water table depth) to describe the high water table stress criteria and the CS factors determined in studies conducted in North Carolina (Table 1). The models were developed using existing field data for SDI and corn and soybean yield data from Ohio. The corn model was tested against data from India and North Carolina and explained 69 % of the relative yield variance for the pooled data, Figure 1. The soybean model explained 66 % of the variance in relative yield for six years of soybean data from Ohio, Figure 2.

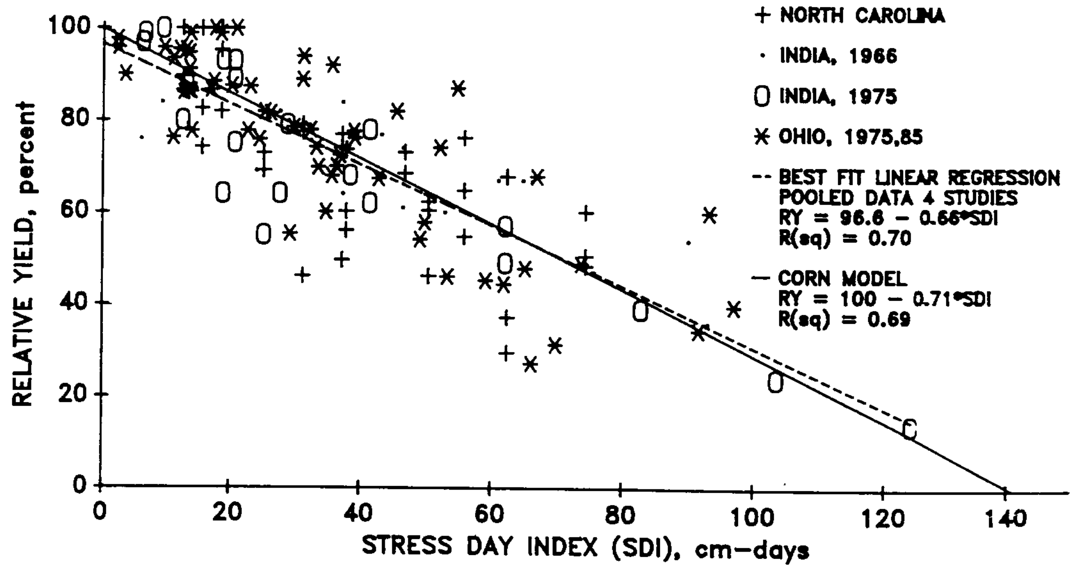

Figure 1. Corn yield SDI model developed from linear regression of corn data from Ohio (Schwab et al., 1975,1985) and CS values from North Carolina. (After Evans et al., 1991)

Using similar procedures, yield - SDI models have been developed to relate corn yield to deficient soil-water conditions (Shaw, 1974) and to planting date delays (Seymour et al, 1992). Combining data from the literature with SDI results presented by Sudar et al. (1979), Evans (1991) developed a yield - SDI model to relate soybean yield to deficient soil-water conditions. Using data from a 3-year study reported by Fike (1974), Evans (1991) developed a yield - SDI model to relate soybean yield to planting delays. The above relationships and submodels are summarized in Table 4.

TESTING AND VALIDATION OF STRESS DAY INDEX MODELS

The water management simulation model, DRAINMOD, (Skaggs, 1978) simulates soil-water conditions in high water table soils. The model considers rainfall, infiltration, surface runoff, drainage, storage and deep seepage to perform a water balance for the soil profile. Hardjoamidjojo and Skaggs (1982) incorporated approximate methods based on the stress-day-index concept to predict corn yield response to stresses caused by excessive and deficient soil-water conditions. The general crop response model represented by these modifications was described by Skaggs et al. (1982) as

$$RY = RY_w \, RY_d \, RY_p \qquad (7)$$

where RY is the overall relative yield for a given year, RY_w is the relative yield that would be obtained if only wet stresses occurred, RY_d is the relative yield that would be obtained if only dry stresses occurred, and RY_p is the relative yield resulting from planting delays only.

Stress	Submodel	Equation No.	Reference	Stress day Factor	Reference	Crop Suscepti-bility	Reference
CORN							
Wet	$RY_w = 100 - 0.71*SDI_w$ $RY_w = 0$	$SDI \leq 141$ (9a) $SDI > 141$ (9b)	9	SEW_{30} (eq. 2)	37	6 stages	8
Dry	$RY_d = 100 - 1.22*SDI_d$ $RY_d = 0$	$SDI < 82$ (10a) $SDI \leq 82$ (10b)	32 normalized by 16	1-(AET/PET) (eq. 3)	32	17 5-day stages	32
Plant Delay	$RY_p = 100 - 0.88*PD$ $RY_p = 130 - 1.60*PD$ $RY_p = 0$	$PD < 40$ (11a) $40 \leq PD \leq 80$ (11b) $PD > 80$ (11c)	31 after 21	Plant Delay Past Optimum (April 15)	31 after 21	2 stages	31, 21
SOYBEAN							
Wet	$RY_w = 100 - 0.65*SDI_w$ $RY_w = 0$	$SDI \leq 154$ (12a) $SDI > 154$ (12b)	9	SEW_{30} (eq. 2)	37	6 stages	8
Dry	$RY_d = 100 - 7.2*SDI_d$ $RY_d = 0$	$SDI < 13.9$ (13a) $SDI \leq 13.9$ (13b)	10 after 43	1-(AET/PET) (eq. 3)	43	10 stages	10 from literature
Plant Delay	$RY_p = 100 - 0.5*PD$ $RY_p = 140 - 1.8*PD$ $RY_p = 0$	$PD \leq 30$ (14a) $30 < PD \leq 78$ (14b) $PD > 78$ (14c)	10 after 13	Plant Delay Past Optimum (May 15)	10 after 13	2 stages	10 after 13

Under severe stress conditions, the relationship given by equation 5 over predicted yield for the Iowa data evaluated by Shaw (1974). Shaw investigated several methods of weighting the stress day factor (eq. 6). The best fit for the Iowa conditions was obtained when an additional weighting factor of 1.5 was applied to the SD factor whenever two or more consecutive 5-day SD factors were 4.5 or greater. The corn data presented herein are evaluated both with and without this severe stress dry weight factor.

Table 4. Relative yield - stress day index relationships used to predict corn and soybean yield response to excessive and deficient soil water conditions and to planting delays.

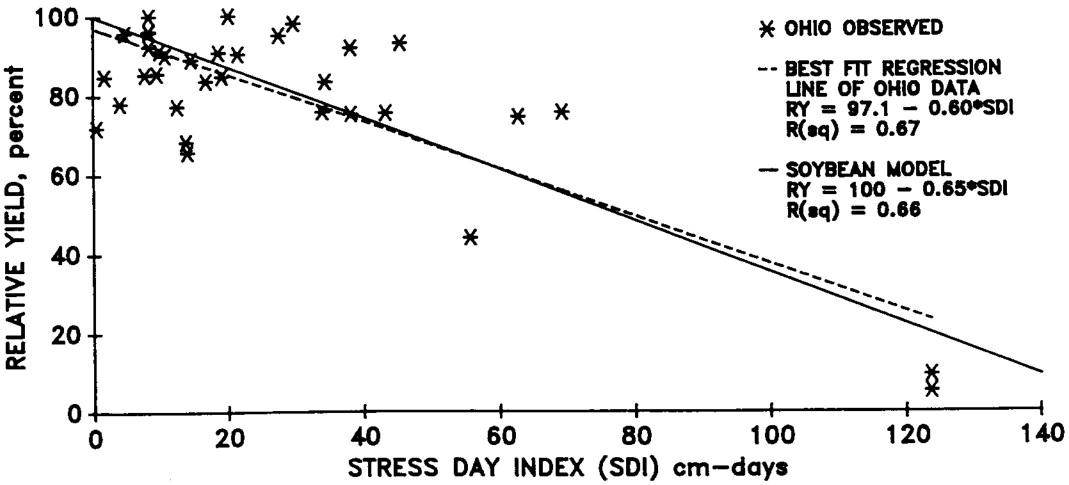

Figure 2. Soybean yield - SDI model developed from linear regression of soybean data from Ohio (Schwab, 1985) and CS values determined in North Carolina. (After Evans et al., 1991).

To compare predicted yields to field measured yields, relative yield may also be expressed as:

$$RY = Y/Y_0 \tag{8}$$

where Y is the measured or observed yield for a given year and Y_0 is the yield that would have occurred in the absence of any soil-water related stresses. Y_0 refers to the base maximum yield that would occur for a consistent combination of agronomic inputs that were not limited by soil - water.

The relative yield components, RY_w, RY_d and RY_p, are assumed to be independent with individual submodels used to calculate each component. Each yield - SDI submodel should be developed and tested independently as discussed in the previous section. The validity of the generalized model (equation 7) should then be tested with field data comprising different types and amounts of soil-water stress.

Observed Yields (Field Validation Data)

Field experiments have been conducted on the Tidewater Research Station near Plymouth, N. C. for over 50 years. The soils at the Tidewater Station are poorly drained. Drainage of most fields has been improved by the installation of parallel ditches or drain tile/tubing so that the site is conducive for evaluation by DRAINMOD. The drainage intensity varies from field to field as discussed by Evans (1991). Even with improved drainage, soil wetness is a problem in some years resulting in planting delays and high water table conditions during the growing season. Droughty conditions develop during periods with below normal rainfall. Corn and soybean are the predominant crops grown on the station.

Five independent studies were identified that provided data suitable to evaluate the SDI relations presented in Table 4. The source and description of these yield data and soil, site, and drainage system parameters for each study were reported by Evans (1991).

Validation Procedure

Overall relative yield (equation 7) was predicted using DRAINMOD with equations 9, 10, and 11 to predict the individual corn yield components and equations 12, 13, and 14 to predict the individual soybean yield components. The corn yield relationship given by equation 10 was evaluated both with (Method 2) and without (Method 1) the severe-stress dry weight factor (WF) (equation 3) described by Shaw (1974, 1978, 1983)(See footnote at bottom of Table 4).

Measured or observed inputs were used for the DRAINMOD simulations wherever possible. These included most of the drainage system parameters, including periods of controlled drainage and subirrigation, hydraulic conductivity, maximum root depth, and Portsmouth soil properties reported by Gilliam et al., 1978). Daily maximum and minimum temperatures and daily rainfall were available from station records. Daily rainfall values were converted to hourly values by the disaggregation methods described by Robbins (1988). Prior to predicting yield, the inputs were calibrated by comparing 12 site-years of measured water table data to predicted values. The calibration procedure involved starting with all known or estimated inputs, running simulations for those fields and periods with water table data, then comparing predicted to observed water tables. This procedure was continued while varying other "estimated" inputs, primarily surface storage, upflux and root depth vs time relationship, until the combination of inputs providing the best water table fit were identified. The RMSE between the observed and simulated water table depths ranged from 12.1 to 21.2 cm/day. The RMSE and AABE of prediction for the pooled data was 15.8 and 11.3 cm/day, respectively. These results indicate that predicted values were in relatively good agreement with observed values. Detailed input values used in the simulations were reported by Evans (1991).

Statistical Procedures

The adequacy of the SDI models was tested by computing average error, average absolute error, root mean square error, and correlation between predicted and observed RY using standard statistical procedures (Evans, 1991). The fit of the predicted yields to the 1:1 line (perfect model) was compared by first determining the best fit linear regression line between predicted and observed yield using the method of least squares (SAS, 1985; Sendecor and Cochran, 1967). The intercept and slope of the best fit regression line was compared to those of the 1:1 line (intercept = 0, slope = 1) using the methods described by Ostle (1963). Finally, the fit of the data (predicted vs observed relative yield) was compared to the 1:1 line. The coefficient of determination, r^2, of this comparison was determined by dividing the best fit regression model sum of squares by the corrected total sum of squares. The corrected total sum of squares for this comparison was the best fit regression model sum of squares plus the error sum of squares $(RY_i - RY'_i)^2$ where RY_i is the relative yield predicted by the simulation model (not regression model) and RY'_i is the observed relative yield.

Predicted Corn Yield

Predicted relative yield components (wet, dry, plant delay), overall predicted relative yield and observed yields were reported in detail by Evans (1991). Space constraints prohibit their presentation here. Observed and predicted relative yield covered the full range of values from 0 to 100 percent, although a majority of values (about 80 percent) occurred in the upper half of the range (RY values between 50 and 100 percent). Over the total period, wet and dry stresses reduced average predicted RY about equally (about 15 percent each). In some years, predicted RY reduction was due entirely to wet or dry stress, but in most years, both wet and dry stresses contributed to the predicted RY reduction.

The AE, AABE, and RMSE for the pooled data are summarized in Table 5. The average error helps identify systematic errors in the prediction method. When the AE is greater than zero indicates that the model may be systematically overestimating observed values or underpredicting if the AE is less than zero. As seen in Table 5, the negative AE indicates yields were slightly underpredicted on average.

The AABE and RMSE provide an indication of the overall performance of the model in terms of the variation between predicted and observed values. The AABE indicates the average magnitude (sign ignored) of the error of each predicted value, with all errors weighted the same. If all errors are about the same magnitude, the AABE and RMSE will be about the same. The RMSE increases above the AABE as the number and magnitude of the poorer predictions increase. Thus, the RMSE provides a better indication of the range of errors.

Combining the results of the AABE and RMSE indicates that both methods had prediction errors of similar magnitude on average (AABE of 7.95 vs 8.89), but, prediction errors involving the severe-stress WF_d (Method 2) had a larger variation within individual observations (RMSE 9.89 vs 13.05).

	Corn SDI Models Method 1 No WF	 Method 2 WF = 1.5	 Soybean SDI Model
Average Error	-1.35	-2.84	-0.44
Average Absolute Error	7.95	8.89	7.46
Root Mean Square Error	9.89	13.05	10.24
Correlation Coefficient r^2	0.808	0.710	0.559
Regression Line	6.71	4.87	20.90
Intercept			
(Different from 0 alpha=0.05)			
no no yes			
Slope	0.889	0.891	0.646
(Different from 1 alpha=0.05)	no	no	yes
1:1 Line forced through origin	no	yes	yes
(Slope Different from 1 alpha=0.05)			

Table 5. Goodness of fit evaluation of predicted to observed overall RY

The sensitivity of the prediction methods to year to year variation in soil-water stresses is best evaluated by comparing correlation between observed and predicted RY. These results are also summarized in Table 5. The intercept of the best fit regression lines for Methods 1 and 2 did not test significantly different from zero (0) at the 5 percent level of significance. The regression lines shown were then forced through the 0 intercept and the slope re-computed and tested against the slope of the 1:1 line (perfect model). The slope of Method 1 was not significantly different from 1 while the slope involving a severe-stress dry weight factor was significantly less than 1 indicating that RY was underpredicted when the severe-stress weight factor was used. Relative yield predicted by Method 1 is plotted against observed RY in Figure 3. Method 1 accounted for nearly 80 percent of the year to year variation in observed corn yield.

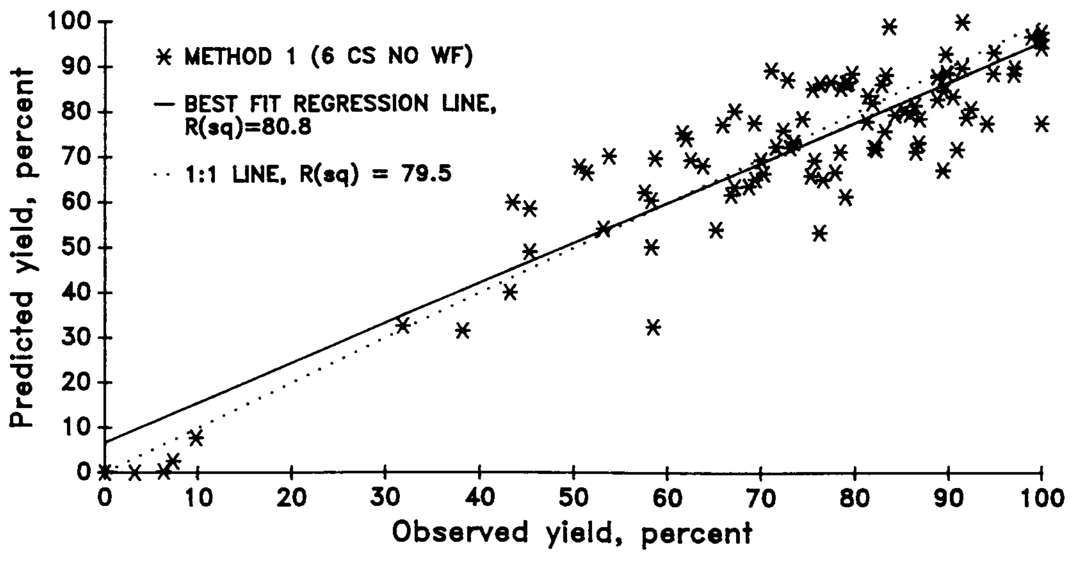

Figure 3. Observed and predicted corn relative yield, best fit regression line for pooled data from all North Carolina data (94 observations) and 1:1 line. (After Evans and Skaggs, 1992).

Predicted Soybean Yield

Soybean RY was predicted by equation 7 using equations 12, 13, and 14 to compute the individual yield components (wet, dry, and plant delay). The individual relative yield components, overall relative yield, and observed relative yield were summarized by Evans (1991).

Predicted and observed RY are plotted in Figure 4. Over 90 percent of the RY values (both predicted and observed) lie between 60 and 100 percent. Relative yields less than 50 percent were observed for only 6 cases. Average error, AABE and RMSE are summarized in Table 5. The AE was -0.44 percent, a slight underprediction.

The intercept of the best fit regression line between predicted and observed RY yield tested significantly greater than zero, Table 5. This could be due to the lack of data points at the lower end of the range. It could also be due to inadequacy of the prediction method. Predictions and trends were good for some years and completely reversed for others. Regardless, the adequacy of the model is best described in terms of correlation to the 1:1 line. The slope of the regression line forced through the intercept did not test significantly differently from 1, but the model explained only 47.9 percent of observed RY variation when compared to the 1:1 line.

The poor correlation between predicted and observed soybean RY may be due to several factors. Soybean can tolerate short term stress with little effect on yield. For example, if dry conditions exist during the pod set period, fewer pods are set. If conditions become more favorable during the subsequent pod fill stage, larger beans can be produced in each pod resulting in about the same yield as would have occurred if more pods had been set but filled with smaller beans. During stressful periods, some physiological processes can even be temporarily halted until more favorable conditions develop (Dunphy, not dated). The simple prediction methods evaluated herein are not capable of predicting these complex physiological recovery processes.

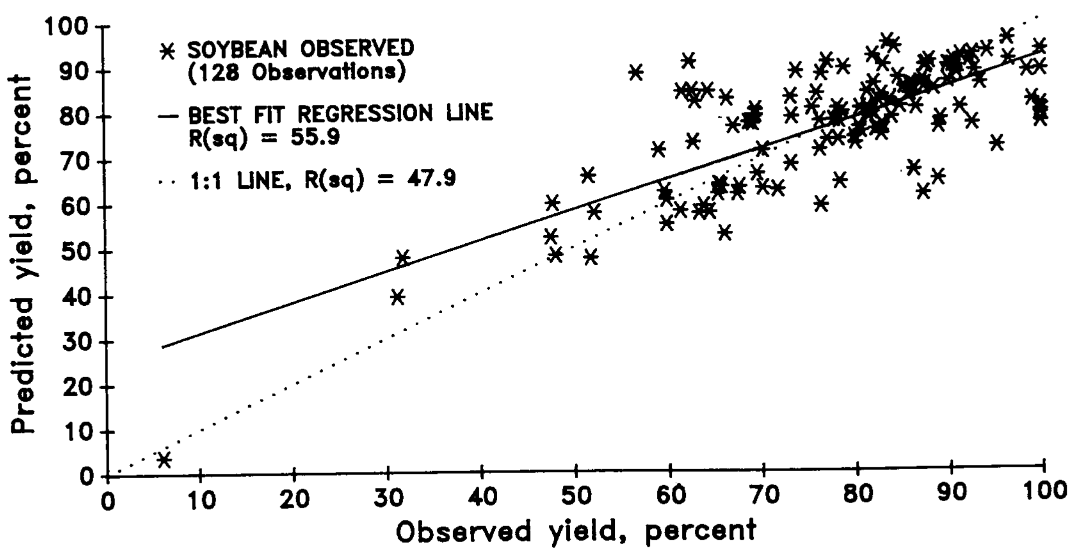

Figure 4. Observed and predicted soybean relative yield, best fit regression line for pooled data from North Carolina (128 observations) and 1:1 line. (After Evans and Skaggs, 1992.)

SUMMARY AND CONCLUSIONS

Crop susceptibility factors were presented for corn and soybean subjected to wet soil-water conditions (wet stresses). Using regression analysis, the crop susceptibility factors were used to develop Stress Day Index Models to predict corn and soybean yield response to high water table conditions.

Corn and soybean relative yield-stress day index models were tested with yields observed in field experiments conducted in eastern North Carolina. The yields were observed over a wide range of weather and soil-water conditions. Daily soil-water stresses resulting from the variable weather conditions were predicted using DRAINMOD. Yield reduction resulting from excessive and deficient soil-water stresses and planting delays were then predicted. All predicted yields were compared to observed yields with the goodness of fit evaluated using several statistical indicators.

The results presented showed that long-term average corn and soybean yields can be predicted with DRAINMOD using SDI models to predict the individual yield components (wet, dry and plant delay). The data tested suggest that severe-stress dry weight factors are not necessary to predict corn yield response to deficient soil-water stresses under traditionally high water table conditions such as exist in eastern North Carolina. Minor modifications to DRAINMOD would facilitate omission of the severe-stress criteria. This would reduce the required yield inputs because several 5-day CS values with the same value could be combined as one input. The methodology used to describe the deficient yield-SDI would then parallel the methods currently used to describe the wet yield-SDI relationship.

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