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DEVELOPING MODELS FOR SIMULATING CORN YIELD AND THE EFFECT OF SUPPLEMENTAL IRRIGATION

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SUMMARY

The objective of this study was to develop models and compare them with already existing models for simulating corn yield and the effect of supplemental irrigation. Ten models were developed using multiple approaches with data on corn yield, soil water, rainfall and temperature. In addition to these models, two other models (earlier published) were used for six locations in U. S. A. and nine locations in five countries including India. Based on actual and simulated yield comparison, high R^2 values, and low standard deviation, four models were selected. These models were also used in simulating the effect of 2.5 cm supplemental irrigation at different growth stages and with variable temperatures. A simple model developed in this study which uses weather data for a three week period (two weeks before and one week after tasseling), is the best model particularly if data limitations are a problem or early prediction is needed. This model simulated 1019 kg/ha additional yield with 2.5 cm of supplemental irrigation at tasseling if the maximum temperature was 37.8°C.

Keywords : Models; Stepwise regression techniques; moisture stress index; temperature; rainfall; yield simulation.

1. Introduction

The greatest income uncertainly involved in producing crops is year

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to year variation in yield. These variations are associated with many factors such as stand, degree of weed control, degree of insect and disease infestation and yearly weather fluctuations. Management systems have been practised in developed and in many developing countries that are able to cope more or less successfully with factors associated with yield variation except for yearly weather fluctuations. Studies of weather-yield relationships have been carried out by agronomists, climatologists, and economists for many years. Excellent reviews have summarized these studies (Benci *et al.* [2]; Newman [9]; Nelson and Dale [8]; Katz [4]; Swanson and Nyankori [15]). In general, two approaches have been used—statistical multiple correlation approaches of yields and weather events for large areas over a time series (Thompson [16]), and detailed physiologic approaches utilizing frequent measurements on a few plants under controlled conditions generally consisting of a few plots and growing conditions (Arkin *et al.* [1]). Studies by Thompson [16] characterize the statistical approach while studies by Arkin *et al.* [1] characterize the physiologic approach. Economists, interested in crop production estimates have usually utilized the statistical models because of data requirements and ease of implementation.

An intermediate modeling approach that simulated actual corn yield weather relationships quite closely was reported by Leeper *et al.* [6, 7]. Nelson and Dale [8] reported on a comparison of modeling methods for several Indian countries. In their study, the Leeper modeling approach produced results equal to or better than those of Thompson [16]; Dale and Hodges]3] derived from data for each of the specific Indiana counties studied. This independent study supports the conclusion of Benci and Runge [2] that models developed by Leeper have application in other parts of the cornbelt. In the USA cornbelt, Leeper's modeling approach generally produced results that agree with experience of Runge and Benci [12]; and Keener *et al.* [5], however their criticism of this modeling method seem justified, particularly since other modeling approaches had not been examined and reported.

The purpose of this paper is to report on a study that examined the original data collected by Leeper to determine if other model forms produced equally good or better results than the models reported by Leeper *et al.* [6, 7] in yield simulation and in quantifying the effect of supplemental irrigation.

2. Model Development

The models of Leeper *et al.* [6, 7] were of the type that utilized plant available stored soil moisture (PASSM), rainfall and temperature in determining corn yield. Previous research by a number of investigators, but documented by Runge and Odell [13] and more thoroughly by Runge [11], established the dependence of corn yields on adequate moisture before, during and after tasseling. Leeper's modeling approach was an extension of these earlier studies and can be reviewed as a bank account approach where stored soil moisture was the initial water supply-account balance, rainfall was viewed as a deposit, while maximum daily temperatures were an indication of demand or withdrawals during the corn growing season.

Data on corn yields, soil water, rainfall and temperature reported for 1969 through 1971 for four locations in Illinois were the basic input data utilized to develop all the models reported here. Other data utilized were open-pan evaporation for Illinois locations that was needed for developing the moisture stress index model. Tasseling dates at two-week intervals were selected to account for early, medium and late tasseling of corn for each location.

Ten models were developed in this study. First two were derived using stepwise regression techniques on the variables obtained by taking square, square root, log and reciprocal terms of variables mentioned in Leeper *et al.* [6] 14-term model. Third and fourth models were developed to test the assumption that rainfall greater than 5 cm per week contributed to runoff and was of little or no use to the plant. Fifth and sixth models were developed using the concept of moisture stress index (MSI) as reported by Shaw and Felch [14]. Seventh and eighth models were developed from variables obtained by dividing the growing season in two periods—six weeks before and four weeks after tasseling date.

Finally the ten week period of the corn growing season selected by Leeper *et al.* [6] was subdivided into three periods for development of models nine and ten.

1. Vegetative and early reproductive period (weeks 1-4)
2. Late vegetative and reproductive period (weeks 5-7)
3. Grain filling and maturity period (weeks 8-10)

Stepwise regression technique was used on the variables including PASSM, total rainfall and average daily maximum temperature for each of these three periods along with their interaction terms. In addition, an 8-term model reported by Leeper *et al.* [7] was used for comparison since it was of the same form as of the Leeper *et al.* [6] 14 term model except it contained fewer interaction terms.

Models developed and used in this study are given in Table 1.

TABLE 1—DESCRIPTION OF MODELS WITH THEIR COEFFICIENT OF DETERMINATION (R^2)

No.	*Model*	R^2
1	$Y = 1566.37 - 83.068\ W - 1.069\ W^2 + 42.9392\ \Sigma\,(R_i t_i)$ $- 8.1130\ \Sigma(R_i t_i^2) + 0.3654\ \Sigma(Th_i t_i)$ $- 0.1013\ \Sigma(Th_i t_i^2) - 0.5014\ \Sigma(R_i Th_i t_i)$ $+ 0.0974\ \Sigma(R_i Th_i t_i^2) - 3.9802\ W\Sigma(R_i t_i)$ $+ 0.7907\ W\Sigma(R_i t_i^2) - 0.0610\ W\Sigma(Th_i t_i)$ $+ 0.0121\ W\Sigma(Th_i t_i^2) + 0.0482\ W\Sigma(R_i Th_i t_i)$ $- 0.0097\ W\Sigma(R_i Th_i t_i^2)$	0.82
2	$Y = 793.484 + 22.8487\ W - 1.0628\ W^2 + 18.5388\ \Sigma(R_i t_i)$ $- 2.8786\ \Sigma(R_i t_i^2) - 0.0585\ \Sigma(Th_i t_i) - 0.0161\ \Sigma(Th_i t_i^2)$ $- 0.2039\ \Sigma(R_i Th_i t_i) + 0.0328\ \Sigma(R_i Th_i t_i^2)$	0.77
3	$Y = 1162.10928 - 13.25948\ (TM_b) - 0.615459\ (W)\ (TM_a)$ $+ 0.748053\ (W)\ (TM_b) - 0.544815\ (W)\ (PR_a)$ $+ 0.083662\ (PR_a)\ (TM_a) - 0.072173\ (PR_b)\ (TM_b)$	0.85
4	$Y = 666.418198 + 21.178452\ (W) - 0.911864\ (W^2)$ $- 57.210942\ (PR_2) - 7.638149\ (TM_2)$ $+ 0.734351\ (PR_2)\ (TM_2)$	0.81

Where:

Y = Simulated yield (bu/acre); 1 bu/acre = 62.8 kg/ha

W = Amount of plant available stored soil moisture (inches) at planting time (PASSM)

R_i = Total weekly rainfall (inches) for the i week

Th_i = Mean of the maximum daily temperature (°F) for the i week

t_i = Week, i = 1 to 10

PR_a = Total rainfall for weeks 1-6

PR_b = Total rainfall for weeks 7-10

TM_a = Average daily maximum temperature for weeks 1-6

TM_b = Average daily maximum temperature for weeks 7-10

PR_2 = Total rainfall for weeks 5-7

TM_2 = Average daily maximum temperature for weeks 5-7

3. Model Comparison

3.1. *USA Locations*

Model performance was tested by simulating corn yields for six USA cornbelt locations. The locations were Columbia, Missouri ; Manhattan, Kansas ; Urbana, Illinois ; Ames Iowa ; Lincoln, Nebraska ; and West Lafayette, Indiana. Yields were simulated for three different fasseling dates each with four different levels of soil water at planting. The highest and lowest simulated corn yield and the pooled standard deviation for the four best models for the July 18 tasseling date and for 25 cm of PASSM at planting were compared. The four best models include Leepers 14 term and 8 term models (models 1 and 2, Table 1). The criteria used to select models 2 and 3 (Table 1) were that the variables included in the model had agronomic basis, were relatively simple, had comparatively high R values, a reasonable range in simulated yield values and relatively low standard deviation.

Model 1 was the best one based on pooled standard deviation and range in simulated corn yields that are in general agreement with actual observations. Model 4 was in an intermediate position while models 2 and 3 were the poorest simulators of these four models.

It is also evident from yield simulation figures of the six locations that Manhattan had the highest pooled standard deviation. The analysis of long term weather records for these locations showed that Manhattam, Kansas had the most variation in weather conditions and the highest frequency of drought. Therefore, simulated yields for the period of 1901-1977 using model I are presented in Figure 1. The mean yield was 6720 kg/ha. The highest yield of 11430 kg/ha was simulated for 1951 and the lowest yield of 754 kg/ha was simulated for the drought year of 1934. These yield simulations assume constant 1969-71 technology, the period of Leeper's original study. Simulated yields of models 1 and 4 were compared for Columbia, Missouri separately since they are the two best models based on criteria discussed earlier. These models have a reasonable 1 : 1 correspondence, however, model 4 predicted somewhat lower yields in poorer years (Figure 2).

3.2 *Locations in other Countries*

Corn yield simulation results of the four best models were compared for Pantnagar, India ; Bogoı, Indonesia ; Rome, Italy ; Christchurch, Palmerstone North, Gisborne and Nelson in New Zealand; and Ukulinga and Cedara in South Africa. Simulated corn yield for these four models were compared for Gisborne, New Zealand (Table 2). A technology

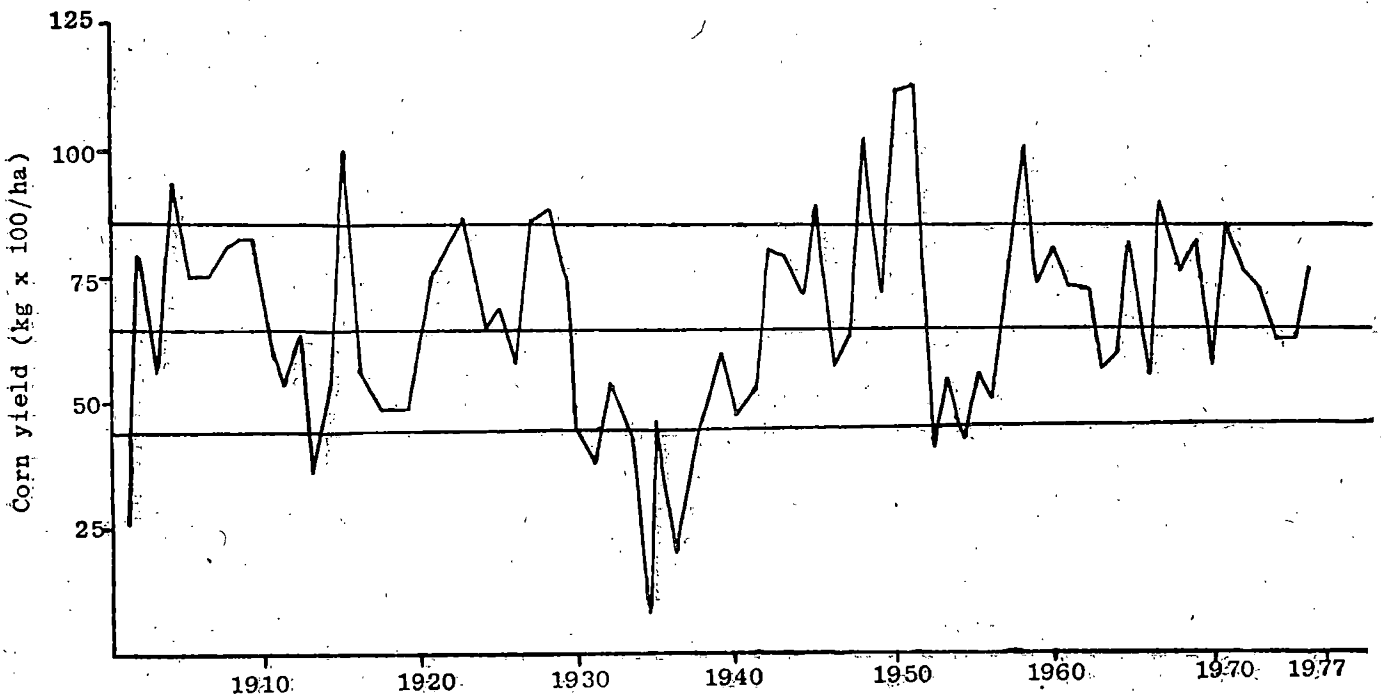

Figure 1. Simulated corn yield for Manhattan, Kansas using model 1 for the July 18 tasseling date and with 25 cm of available soil water at planting.

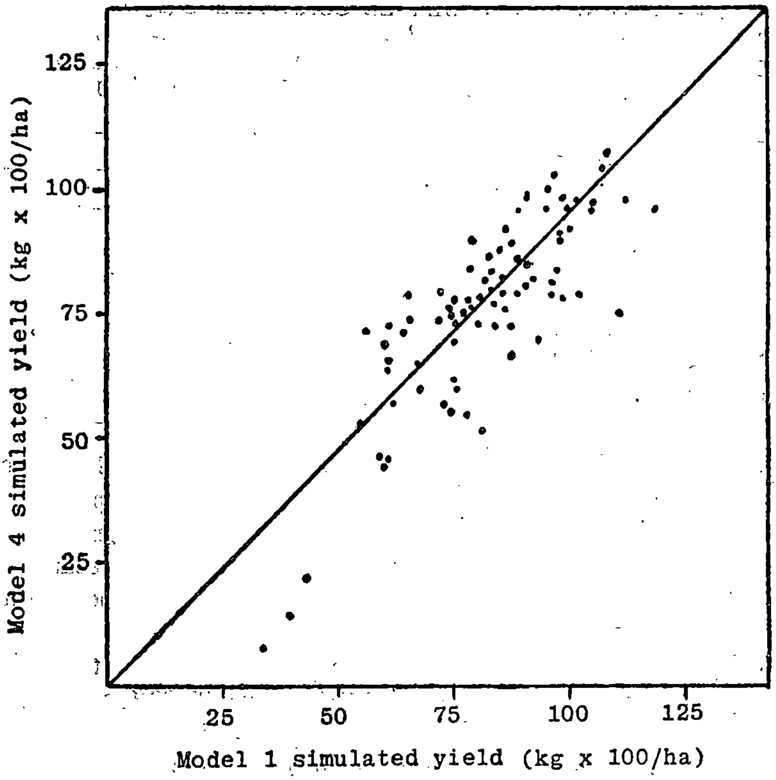

Figure 2. Comparison between model 1 and model 4 simulated corn yields for Columbia, Missouri.

TABLE 2—SIMULATED CORN YIELDS (kg × 100/ha) FOR GISBORNE, NEW ZEALAND FOR DECEMBER 29 TASSELING DATE AND 15 cm OF PLANT AVAILABLE STORED SOIL MOISTURE AT PLANTING

Model	*Year*				
	1971	*1972*	*1973*	*1974*	*1975*
1	138	122	132	126	126
2	134	126	119	124	123
3	135	150	132	145	136
4	110	113	107	116	111

conversion factor of 0.31 (Runge and Benci, [12] was used for comparing actual and simulated yield for four years for Pantnagar, India (Table 3). The technology conversion factor of 0.31 means all model yield simulations were multiplied by 0.31.

TABLE 3—ACTUAL AND SIMULATED CORN YIELDS (kg × 100/ha) FOR PANTNAGAR, INDIA FOR AUGUST 18 TASSELING DATE AND 25 cm OF PLANT AVAILABLE STORED SOIL MOISTURE AT PLANTING. (A TECHNOLOGY CONVERSION FACTOR OF 0.31 IS USED)

Year	*Actual Yields*	*Simulated Yield by Models*			
		1	*2*	*3*	*4*
1965	27	27	25	32	32
1966	32	29	26	20	25
1970	17	21	26	4	36
1972	16	28	33	4	31

Simulation results from the locations other then in U.S.A. seem to overestimate corn yields. In New Zealand where the temperature was low (average temperature is 21°C) all the models had a tendency to over-estimate yields even with low soil water. Some lack of agreement with actual data should be expected since models were developed from the data of experimental field with adequate management.

Another aspect to consider in evaluating these results is that average temperature of the growing season in Urbana was 27-32°C and the growing season started with recharged soil profiles. Soil moisture depletion occured as the crop grew. Crops grown during the monsoon season particularly in India often were seeded when rainfall began and the soil was recharged as the crop grew.

4. Simulating the Effect of Supplemental Irrigation

Corn yield simulation results for 2.5 cm of supplemental irrigation at different growth stages with variable air temperature and PASSM are discussed in this section. Of the four models used in this study, model 4 as described in the previous section was the simplest model and simulation results for this model are discussed first. Partial derivative of this model with respect to rainfall is given by

$$\delta Y/\delta PR_8(TM_2) = -57.210942 + 0.734351\ (TM_2) \qquad (1)$$

Model 4 quantifies the effect of irrigation during a three-week period of tasseling (two weeks before and one week after tasseling). If the average maximum daily temperatures during this period were 29.4, 32.2 and 37.8°C, an application of 2.5 cm of water increased simulated corn yield by 327, 558 and 1019 kg/ha, respectively. On the contrary no beneficial effect was simulated for adding 2.5 cm water during this period if average maximum temperature was only 25.5°C.

Model 2 could simulate yield changes for adding supplemental water in any of the 10 weeks, while model 3 could simulate for two periods—pre-tasseling and post-tasseling. The partial derivatives of model 3 with respect to rainfall for each of the two stages (weeks 1—6, weeks 7—10) are presented in equations 2 and 3.

$$\delta Y/\delta PR_a(W, TM_a) = -0.5448\,(W) + 0.0837\,(TM_a) \qquad (2)$$

$$\delta Y/\delta PR_b(W, TM_b) = -0.0722\,(TM_b) \qquad (3)$$

With 15 cm PASSM at planting, additional yield of 320 and 270 kg/ha were simulated by an application of 2.5 cm of water during the late vegetative and early reproductive stage if the maximum temperature during this period was 37.8°C and 32.2°C, respectively. The simulated yield changes for these two temperature levels were 213 and 132 kg/ha if PASSM at planting was 25 cm. No additional corn yield was expected when water was applied during this period if the maximum temperature was 3.9°C and 18.4°C for 15 and 25 cm PASSM at planting, respectively.

Equation 3 indicates that additional water during the grain filling and early maturity period (weeks 7 through 10) will reduce yields. This is due to the negative coefficient for temperature in the partial derivative. This result has no agronomic basis that we are aware of. The lack of a plausible agronomic interpretation decreased the confidence in this model and therefore its usefulness in simulating yields is questionable.

Models 1 and 2 (Table 1) were of similar form, however, the model 1 is more complicated. The partial derivatives of models 1 and 2 with respect to rainfall are given in equations 4 and 5, respectively.

$$\begin{aligned}\delta Y/\delta R(i, Th, W) = {} & 42.9392\,(t_i) - 8.1130\,(t_i^2) - 0.5014\,(Th_i)\,(t_i) \\ & + 0.0974\,(Th_i)\,(t_i^2 - 3.9802\,(W)\,(t_i) \\ & + 0.7907\,(W)\,(t_i^2) + 0.0482\,(W)\,(Th_i)\,(t_i) \\ & - 0.0097\,(W)\,(Th_i)\,(t_i^2)\end{aligned} \qquad (4)$$

$$\begin{aligned}\delta Y/\delta R(t, Th) = {} & 18.5388\,(t_i) - 2.8786\,(t_i^2) \\ & - 0.2039\,(Th_i)\,(t_i) + 0.0321\,(Th_i)\,(t_i^2)\end{aligned} \qquad (5)$$

These partial derivatives were solved for three different temperature levels 23.9°C, 29.4°C and 35.0°C. The partial derivative of model 2 does not contain the PASSM term, therefore, response in simulated corn yield due to additional water are independent of this factor (Figure 3).

Model 1 was solved for three temperature levels at 15, 20, 25 and 30 cm of PASSM at planting and simulation results for 15 cm PASSM at planting are given in Figure 4.

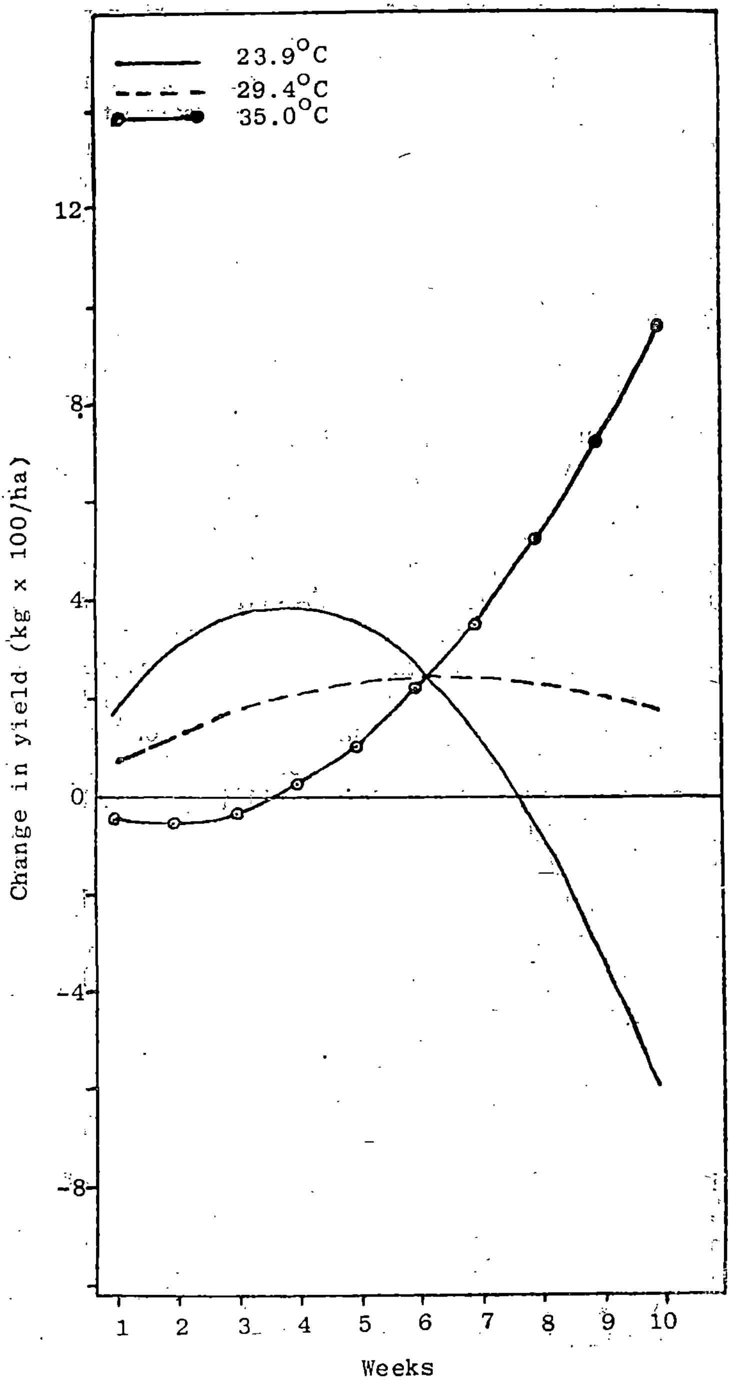

Figure 3. Effect of 2.5 cm supplemental irrigation during different weeks of the growing season on model 2 simulated corn yields for indicated maximum temperatures.

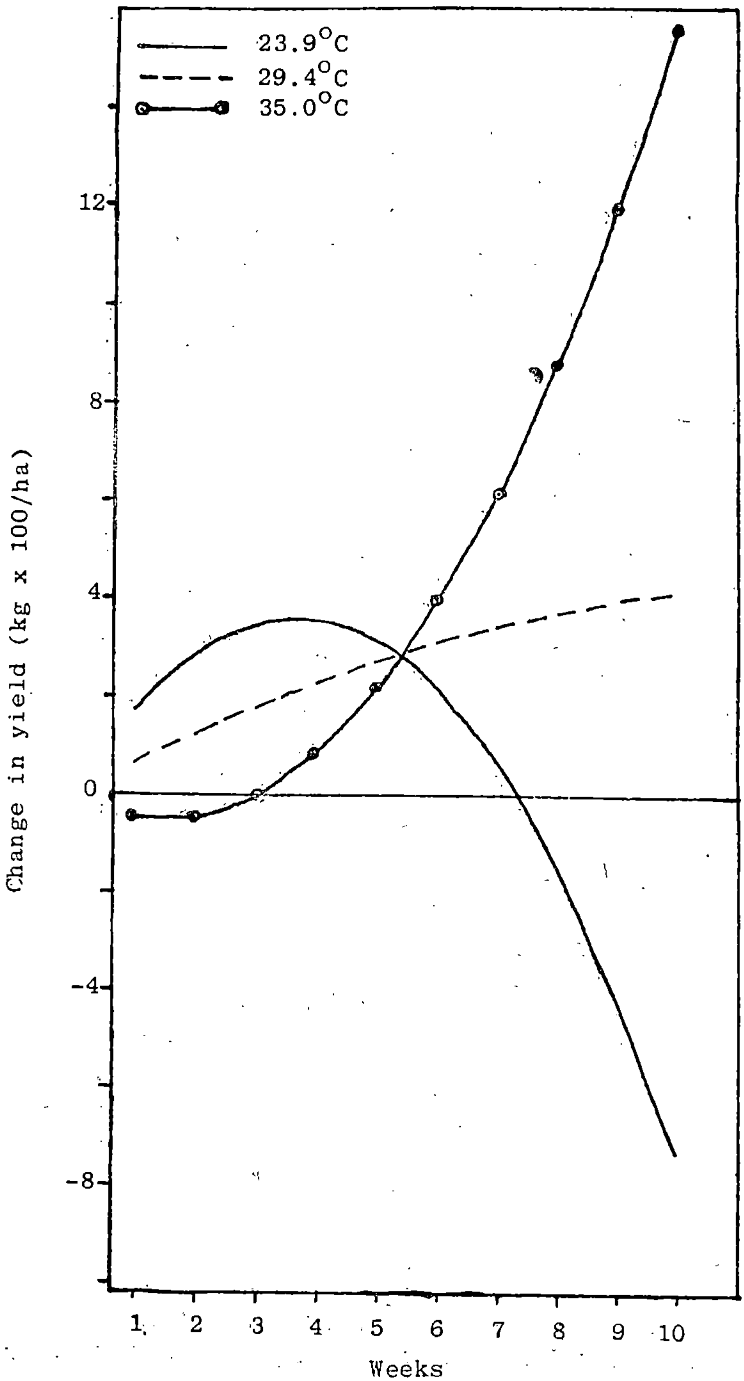

Figure 4. Effect of 2.5 cm supplemental irrigation during different weeks of the growing season on model 1 simulated corn yields for indicated maximum temperatures with 15 cm available soil water at planting.

Results were simulated for different tasseling dates, however, the results assuming 18 July as the average tasseling date are discussed here. In the U.S. corn belt the maximum temperature usually ranged between 24 and 30°C particularly during the early stage of the growing season. Both models 1 and 2 simulated additional yield when water was applied in the early part of the growing season for this temperature range.

We already know that moisture and temperature relationships on corn yield are important during the grain filling and early maturity period (weeks 7-10). Conceptually this results at least in part because water stored in the soil becomes depleted and more direct yield relationships exist due to rainfall and temperature variations from year to year during this part of the growing season. Therefore simulated yields in any week during this period that are more responsive to an application of 2.5 cm water has an agronomic basis.

Both models 1 and 2 were used to simulate the effect of additional water for previous years reporting low, normal and above normal corn yields using historical data for the six U. S. locations. The locations and year included Columbia, Missouri (1901 thru 1977); Manhattan, Kansas (1901 thru 1977); Urbana, Illinois (1903 thru 1977); Ames, Iowa (1901 thru 1977); Lincoln, Nebraska (1922 thru 1977) and West Lafayette, Indiana (1901 thru 1977). Results were obtained for different tasseling dates however results for the July 18 tasseling date and for 15 cm of PASSM present at planting for all these locations and years were critically examined. The simulation results for all the six U.S. corn belt locations reflected a similar pattern. Therefore only results for Columbia, Missouri are discussed. Results of highest, lowest and average effect with standard deviation for the period of 1901-1977 were supported by the earlier observation that addition of water in the late growing period were associated with yield changes if the temperature was also above average. The largest simulated yield change for applying 2.5 cm water occurred in the tenth week of 1934 when the maximum temperature was 38.9°C and the total rainfall was only 1.2 cm. No additional yield was simulated for applying water in a week with low temperature and high rainfall. Such an example occured in the tenth week of 1917 when the maximum temperature was 25.3°C and rainfall was 4.8 cm. In fact yield decreased with an application of 2.5 cm water in that week.

5. Conclusions

(i) If data limitations are a problem or early yield simulation is required, model 4 may be useful since it uses information for a three week period near tasseling. Data inputs to drive this model are generally available except for plant available stored soil moisture which can be estimated or derived by using soil moisture balance models (e.g. Ritchie [10] model).

(ii) Model 4 simulated 327, 558 and 1019 kg/ha additional corn yields with 2.5 cm supplemental irrigation at tasseling if the maximum temperatures were 29.4, 32.2 and 37.8°C respectively.

(iii) The effect of supplemental irrigation on simulated corn yield was low during the vegetative period it increased during the reproductive and early grain filling period and started declining with the onset of maturity.

(iv) Lower yield was simulated by supplemental irrigation if there was high rainfall and low temperature.

(v) The effect of supplemental irrigation on simulated corn yield was more for soils with low PASSM.

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