IRRIGATION MANAGEMENT STRATEGIES FOR HUMID REGIONS

L. C. Hammond R. B. Campbell E. D. Threadgill
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The need to irrigate many humid region soils for high crop yields has been well documented (Bruce et al. 1980, Butson and Prine 1968, Sheridan et al. 1979, van Bavel and Verlinden 1956, and van Bavel and Carreker 1957). Growth in irrigation farming in the southeastern United States has outpaced the accumulation of research data necessary for the development of irrigation practices which maximize profits. However, a growing worldwide demand for food and fiber coupled with an energy crisis has stimulated research on efficient irrigation management. In humid regions, where irrigation water is not necessary for salt control, the goal is to maximize the evapotranspirational use of irrigation and rainfall while minimizing the leaching loss of water, fertilizers, and pesticides during the crop-growing season. A near ideal water situation would be a soil water profile near maximum capacity at planting, but depleted by 50% or more at harvest, and a season-long rainfall and irrigation distribution pattern producing no plant water stress and no drainage loss. Crop yields have been shown to increase linearly with actual evapotranspiration (ET) until potential ET has been attained (deWit 1958, Hanks 1974, Musick and Dusek 1980, Skogerboe et al. 1979, and Tanner 1981). This response is not surprising in view of the fact that the same stomatal barrier is encountered by both CO_2 and water vapor during photosynthesis and transpiration. Low stomatal resistances are necessary for photosynthetic processes to function at optimum levels within constraints of other factors (solar radiation, temperature, nature and growth stage of crop, and CO_2 levels).

A series of strategies will be necessary to approach the above goal of 100% efficiency in irrigation water use. The simple question of when to irrigate and how much water to apply leads to a myriad of factors and decision-making consequences. We use the term "strategy" to encompass the complex and dynamic decision-making process which leads to a series of irrigation scheduling practices appropriate to the ever-changing environmental and economic conditions encountered by the farmer in producing a crop.

The purpose of this paper is to discuss strategies in irrigation scheduling resulting from recent experiences in the southeastern United States.

METHODS

An irrigation management field experiment on corn was established in 1979 at Gainesville, Florida, on Lake fine sand--an excessively drained, coated, thermic, Typic Quartzipsamment. Funk G-4507 corn hybrid was planted on March 13, 1979 in 90-cm rows at a population of 71,000 plants/ha. A broadcast application of 4-3.5-13.3 (NPK) fertilizer (1120 kg/ha) was incorporated in

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the top 10 cm of soil one week ahead of planting. Two sidedressings with NH_4NO_3 gave a total N application of 200 kg/ha. A solid set, impact sprinkler system delivering 2.54 cm of water per hour was used to apply the desired irrigation quantities during early morning hours when winds were calm. The plots were 13.7 m x 13.7 m in size and arranged in a randomized complete block design with four replications. Water management treatments were: (1) rainfed; (2) irrigation, light rate (0.8-1.9 cm); (3) irrigation, medium rate (1.7-2.5 cm); (4) irrigation, light rate, and only after beginning tassel; and (5) irrigation, light rate, and only up to beginning tassel. The maximum irrigation rates were used after day 68. Irrigation was scheduled on treatment 2 by a water budget procedure[1/] using calculated (Jensen and Haise 1963) daily ET rates. Irrigations were scheduled on treatments 3, 4, and 5 when pore-water pressures became more negative than minus 200 mb at 15-cm depths. In all irrigation treatments, the basic strategy was to refill part of the depleted soil profile, thus leaving some storage to be filled by rainfall. However, no effort was made to maintain a constant or even a known allowable depletion except in the model scheduling of treatment 2 where the allowable depletion was varied from 95% the first two weeks to 50% by midseason and 60% the last two weeks (based on the developing root zone).

Response to water management was determined as yield of corn grain. A simple water balance simulation (Rao et al. 1976, 1981) provided estimates of daily and seasonal ET and drainage, and daily soil profile water contents. Required model inputs include calculated daily ET rates, measured soil water characteristics (water contents at field capacity and permanent wilting, hydraulic conductivity and water redistribution time), and root depth with time. In the water balance simulations, daily ET values were obtained from monthly potential ET rates calculated by the Penman method from long-term weather records and handbook tables of extraterrestrial radiation. An arbitrary 10% downward adjustment of the ET rate was made for an incomplete crop canopy (0-25 days) during the early part of the season, and a 10% upward adjustment was made for later in the season (after 40 days). Measured field capacity and permanent wilting volume percentages were 7.5 and 2.2, respectively, to the 28-cm depth, and 6.5 and 2.2 from 28 cm to maximum root depth at 180 cm. The maximum soil water content during infiltration was set at 20% by volume and a 5-day redistribution time was used.

YIELDS AND WATER BALANCE

Rainfall and irrigation distributions for 3 of the 5 treatments are shown in Fig. 1. In addition, the estimated daily water losses by drainage from the 180-cm soil profile are shown. Changes in the comparative water inputs and the drainage losses reflect increasing rooting depth with time. Irrigation treatments 2 and 3 produced drainage at times when no drainage occurred from the rainfall treatment. Grain yields and complete seasonal water balance data for all treatments are given in Table 1. Drainage, ET, and profile water depletion are estimates from the simulation procedure. Grain yields were low and variable due to fertility problems associated with earlier experiments on the field site. Although the relationship of yield and seasonal irrigation and ET is less precise than in some of our other studies, the overall findings will be useful to our discussion of irrigation management strategies.

The effect of ET, irrigation, and rainfall over a 7-day period on pore water pressure in the profiles of treatments 2 and 3 is shown in Table 2. These data show the effect of treatment on the initial water pressure distribution, depth of restoration of the depleted profiles by different irrigation amounts, and depths of wetting following rainfall. Treatments 2 and 3 had

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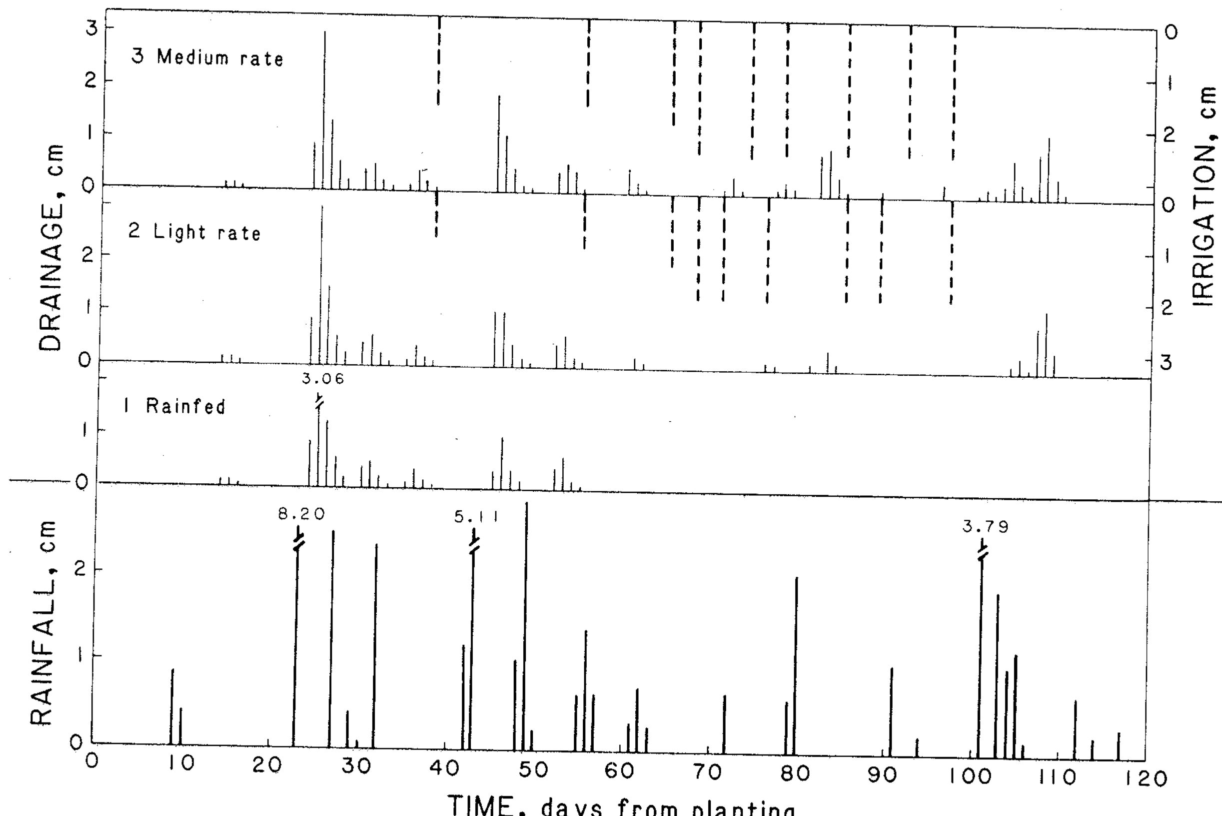

Fig. 1. Rainfall, Irrigation, and Drainage (from 180 cm Profile) in Three Water Management Treatments on Corn, Gainesville, 1979.

been irrigated 8 and 5 days earlier, respectively. The calculated available water depletion on June 17th was 44% and 27% for treatments 2 and 3, respectively, assuming a root depth of 164 cm. Differences in depth of wetting on June 24 and the resultant differences in drainage from subsequent rainfalls as shown in Fig. 1 (days 100 to 110) illustrate the water-conserving value of a partial refilling of the depleted profile with each irrigation.

Table 1. Effect of Water Management on Seasonal Water Balance Components and Yield of Corn, Gainesville, 1979

Treatment	ET	Irrig.[a]	Soil water depletion[b]	Drainage	Grain yield
	(cm)				(kg/ha)
(1) Rainfed	36.8	-	6.1	12.7	1430
(2) Irrigated, light	42.9	14.6	3.1	18.2	5120
(3) Irrigated, medium	42.9	20.6	3.1	24.2	5190
(4) Irrigated, stress[c]	42.9	12.8	3.1	16.4	4250
(5) Irrigated, stress[c]	37.5	2.1	5.9	14.1	2690

[a]Rainfall, 43.4 cm.

[b]Soil profile water content to maximum root depth at planting (12 cm) minus content at crop maturity.

[c]Irrigation started only after beginning tassel on treatment 4 and terminated at that time on treatment 5.

Table 2. Soil Water Pressure Distribution under Two Irrigation Treatments on Three Dates in 1979

	Soil water pressure (negative)[a]					
	Treatment 2			Treatment 3		
Depth	6/17	6/19	6/24	6/17	6/19	6/24
(cm)	(millibars)					
15	354	75	77	445	67	98
30	170	65	68	114	51	76
45	128	147	61	79	70	73
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120	-	-	126	-	-	44
150	-	-	103	-	-	43

[a]Irrigation of 1.9 and 2.5 cm on treatments 2 and 3, respectively, on June 18. Rainfall: 3.8 cm on June 21 and 1.9 cm on June 23.

Grain yield response to irrigation and to ET is shown in Fig. 2. The regression coefficients are similar to those found by us in other experiments, as well as those reported by others (Musick and Dusek 1980, Morey et al. 1980, Rhoads and Stanley 1973, Robertson et al. 1973, Skogerboe et al. 1979, and Stewart et al. 1975). The relationships shown in Fig. 2 are apparently typical of crop response to water supply (Stegman et al. 1980) and will be used as a focal point for our discussion of irrigation strategies.

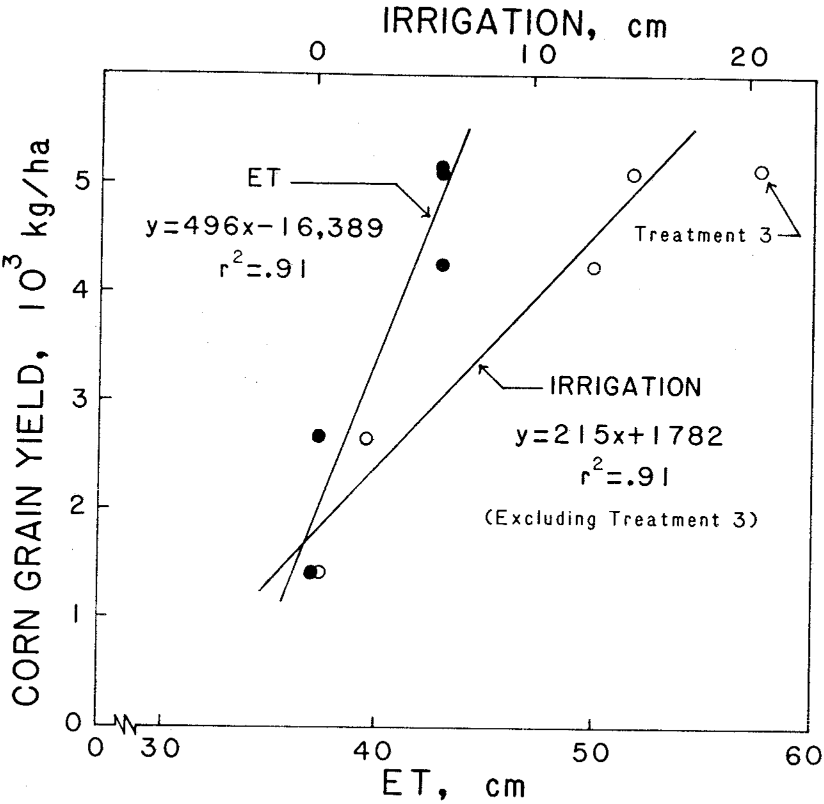

Fig. 2. Grain Yield in Relation to Seasonal Irrigation and Simulated ET, Gainesville, 1979.

The relationships in Fig. 2 are in agreement with theoretical expectations. If all applied water was used as evapotranspiration, the two curves would be superimposed. It does not appear likely that the irrigation function would ever be larger than the ET function. The smaller slope of the irrigation function is an indication of the inefficiency of irrigation management for the particular season. In fact, an estimate of the fraction of applied water which was used as ET is given by the ratio of regression coefficients (21.5/496 = 0.43). Likewise, individual treatment estimates are given by the ratio of the increase in ET and the seasonal irrigation amount (for treatment 3, 6.1/20.6 = 0.30). The latter calculations are more appropriate if, as indicated by Stegman et al. (1980), the irrigation function is typically curvilinear and curves away from the ET function as irrigation depths increase. In 1980 Georgia experiments, an estimated 67% of irrigation was used to increase ET. A comparable value of 70% was obtained in Florida in 1980 from irrigation and ET production functions of 350 and 500 kg/ha-cm, respectively. Because of rainfall uncertainty in the southeastern U.S., it is not possible to avoid an appreciable loss of irrigation water by deep percolation.

Production functions like those in Fig. 2 are useful in several ways. First, the general relationship of crop yield to irrigation must be determined through experience and research in order to develop economical water management systems and practices for particular soil-climate-crop systems. The researcher investigates the processes affecting the relationship and tests experimental systems and practices against the historical data base. The farmer develops management strategies to achieve what has been shown to be possible and more. Policymakers and planners need the above information in developing and allocating resources. For humid conditions, it appears that the linear portion of the irrigation function should be the working basis for irrigation scheduling strategies. The goal should be to achieve the yield potential associated with maximum ET while minimizing non-ET losses of applied water. As others have shown (Phene and Beale 1976, Rawlins and Raats 1975, Skogerboe et al 1979, and Stegman et al. 1980) and as the data in Table 2 and Fig. 2 show, relative to treatment 3, irrigation must be scheduled frequently and at rates which leave some unfilled soil storage for following rainfall. Non-ET losses of water may interact with the crop and soil to cause yield reductions through leaching of nutrients and poor soil aeration (Campbell and Phene 1977, Campbell and Moreau 1979, and Skogerboe et al. 1979).

The ET function can be a family of curves depending on the sequencing of ET deficits during the growing season (Stegman et al. 1980). The latter also affects the scatter of data points for the irrigation function. However, a mean ET function based on near optimum ET deficit sequencing is a valuable function. It represents a goal and a standard against which strategy results can be tested. Moreover, this function as well as others in the family of functions predicts the yield reduction for given ET deficits.

Water management implications of these two types of functions have been discussed in detail by Stegman et al. (1980). It is encouraging that recent results of water management studies conducted in the humid southeastern U.S. parallel the more extensive data from subhumid and semiarid regions and can be subjected to similar analysis and evaluation. Differences in water management goals and strategies between these regions should, in the main, reflect differences in available water resources and rainfall uncertainties.

Additional water management strategy considerations will be mentioned only briefly. Strategies related to fractional replenishment of the depleted soil profile and deficit irrigation cannot be isolated from the question of irrigation timing. A strategy of variable timing throughout the crop season would be expected to be most appropriate to the temporal changes in canopy coverage, plant rooting depth, and plant growth stage-related sensitivity to water stress. Timing may be based on the plant condition (water potential, observable wilting, etc.), soil condition (water potential, water content, and water depletion level and distribution in the root zone), and estimated ET (from pan evaporation or from real time of historical meteorological data, solar radiation, vapor pressure, wind speed, and temperature). Crop condition is the basic consideration since the goal is to supply the water needs of the plant for maximum photosynthesis. In the absence of measurements of crop and soil conditions, observation of indicator plants (weeds, sensitive varieties or cultivars) or indicator areas in the field can be helpful in determining when to irrigate.

Adapting the cropping pattern and sequence to irrigation farming is another aspect of management strategy. High capital and operating costs of irrigation equipment may require changes such as multiple cropping--a practice currently being recommended in Georgia as a means of reducing the risk of irrigation farming.

System design impacts vary strongly on irrigation strategies directed toward the goal of full ET for the plant canopy and no drainage of water below the root zone. A high degree of application uniformity is a necessity. Thus, irrigation may need to be scheduled at night when wind is less of a factor. Although many systems are large (100 ha or more), smaller center-pivot systems (20 ha or less) are becoming more common throughout the southeastern

U.S. due to small field size and rolling topography. These smaller systems may require 24 hours or less per revolution while large systems may require 48 hours or more. Both are usually designed to replace an expected accumulated ET depth during a revolution. Frequently, the speed (and thus, output) can be varied to meet variable ET demands and permit short shut-down periods between revolutions. A system not able to meet ET demand during the designed revolution time forces a deficit irrigation practice which will not supply water needs during an extended drought. For the March-June period in South Georgia, Sheridan et al. (1979) have found that in one out of 2 years there will be at least 21 consecutive days with less than 0.6 cm of rainfall on any day. Attempts to minimize underdesigned system problems by beginning irrigation ahead of need results in water loss during rainfall intervals and water stress damage during long droughts. Special soil and climate conditions in Nebraska permitted the successful use of high-frequency irrigation at less than ET demand rates (Fischbach and Somerhalder 1974). However, discussions with Cooperative Extension Service personnel and farmers revealed that substantial yield losses were experienced in 1977, 1980, and 1981 in Georgia due to delaying the initial irrigation for 2-3 days and then applying water at ET demand rates during an extended drought. The soil profile initially became so dry that the system simply could not "catch up." Consequently, only the upper portion of the root zone had adequate moisture for the duration of the drought. This is typical of center-pivot irrigation systems (Stegman et al. 1980), and more research data are needed to resolve this particular design and management problem under humid conditions.

CONCLUSIONS

There are two production functions for consideration in developing irrigation strategies and in evaluating the successes or failures of strategies used. The ET function (yield per unit of water used in seasonal ET) should be reasonably constant from season to season and represent a maximum or goal to achieve in irrigation management. Moreover, this function predicts the losses in yield to be expected per unit of seasonal ET deficit. In marked contrast, the irrigation function (yield per unit of irrigation water applied during the season) is highly variable with season and with the irrigation treatments used to find the function. Nevertheless, average irrigation function values (in the linear range) are needed in assessing the economic potential of irrigation farming. Essential elements of irrigation management strategies for humid regions include: variable scheduling practices with stage of growth and crop condition, irrigation to replenish a fraction of the water-depleted profile, irrigation to prevent plant water stress, and the development of an intensive overall crop management scheme attuned to the dynamic soil-plant-climate system.

REFERENCES

1. Bruce, R.R., J.L. Chesness, T.C. Keisling, J.E. Pallas, Jr., D.A. Smittle, J.R. Stansel and A.W. Thomas. 1980. Irrigation of crops in the southeastern United States: Principles and practice. USDA-SEA. ARM-S-9/May 1980. 54 p.

2. Butson, K.D. and G.M. Prine. 1968. Weekly rainfall frequencies in Florida. Florida Ag. Exp. Sta. Circular S-187. April 1968. 41 p.

3. Campbell, R.B. and R.A. Moreau. 1979. Ethylene in a compacted field soil and its effect on growth, tuber quality, and yield of potatoes. Amer. Potato J. 56: 199-210.

4. Campbell, R.B. and C.J. Phene. 1977. Tillage, matric potential, oxygen and millet yield relations in a layered soil. TRANS. of the ASAE 20: 271-275.

5. deWit, C.T. 1958. Transpiration and crop yields. Versl. Landbouwkd. Onderz. 64.4. 88 p.

6. Fischbach, P.E. and B.R. Somerhalder. 1974. Irrigation design requirements for corn. TRANS. of the ASAE 17: 162-165, 171.

7. Hanks, R.J. 1974. Model for predicting plant yield as influenced by water use. Agron. J. 66: 660-664.

8. Jensen, M.E. and H.R. Haise. 1963. Estimating evapotranspiration from solar radiation. J. Irrig. Drain. Div., ASCE 89: 15-41.

9. Morey, R.V., J.R. Gilley, F.G. Bergsrud and L.R. Dirkzwager. 1980. Yield response of corn related to soil moisture. TRANS. of the ASAE 23: 1165-1170.

10. Musick, J.T. and D.A. Dusek. 1980. Irrigated corn yield response to water. TRANS. of the ASAE 23: 92-98, 103.

11. Phene, C.J. and O.W. Beale. 1976. High-frequency irrigation for water management in humid regions. Soil Sci. Soc. Amer. J. 40: 430-436.

12. Rao, P.S.C., J.M. Davidson and L.C. Hammond. 1976. Estimation of nonreactive and reactive solute front locations in soils. In Residual Management by Land Disposal. Proc. Hazardous Waste Residue Symposium. Tucson, AZ. p. 235-242.

13. Rao, P.S.C., J.M. Davidson and R.E. Jessup. 1981. Simulation of nitrogen behavior in the root zone of cropped land areas receiving organic wastes. In Simulation of Nitrogen Behavior in Soil-Plant Systems (edited by M.J. Frissel and J.A. vanVeen). Pudoc, Wageningen, The Netherlands. p. 81-95.

14. Rawlins, S.L. and P.A.C. Raats. 1975. Prospects for high-frequency irrigation. Science. 188: 604-609.

15. Rhoads, F.M. and R.L. Stanley, Jr. 1973. Response of three corn hybrids to low levels of soil moisture tension in the plow layer. Agron. J. 65: 315-318.

16. Robertson, W.K., L.C. Hammond, G.K. Saxena and H.W. Lundy. 1973. Influence of water management through irrigation and a subsurface asphalt layer on seasonal growth and nutrient uptake of corn. Agron. J. 65: 866-868.

17. Sheridan, J.M., W.G. Knisel, Jr., T.K. Woody, III and L.E. Asmussen. 1979. Seasonal variation in rainfall and rainfall-deficient periods in the Southern Coastal Plain and Flatwoods regions of Georgia. Georgia Agr. Exp. Sta. Res. Bull. 243. 73 p.

18. Skogerboe, G.V., J.W.H. Barrett, B.J. Treat and D.B. McWhorter. 1979. Potential effects of irrigation practices on crop yields in Grand Valley. EPA-600/2-79-149. 193 p.

19. Stegman, E.C., J.T. Musick and J.I. Stewart. 1980. Irrigation water management. In Design and operation of farm irrigation systems (edited by M.E. Jensen) ASAE Monograph 3. Amer. Soc. Agric. Eng., St. Joseph, Michigan. p 763-816.

20. Stewart, J.I., R.D. Misra, W.O. Pruitt, and R.M. Hagan. 1975. Irrigating corn and grain sorghum with a deficient water supply. TRANS. of the ASAE 18: 270-280.

21. Tanner, C.B. 1981. Transpiration efficiency of potato. Agron. J. 73: 59-64.

22. van Bavel, C.H.M. and F.J. Verlinden. 1956. Agricultural drought in North Carolina. North Carolina Ag. Exp. Sta. Tech. Bull. 122. June 1956. 60 p.

23. van Bavel, C.H.M. and J.R. Carreker. 1957. Agricultural drought in Georgia. Georgia Ag. Exp. Sta. Tech. Bull. N.S. 15. 41 p.

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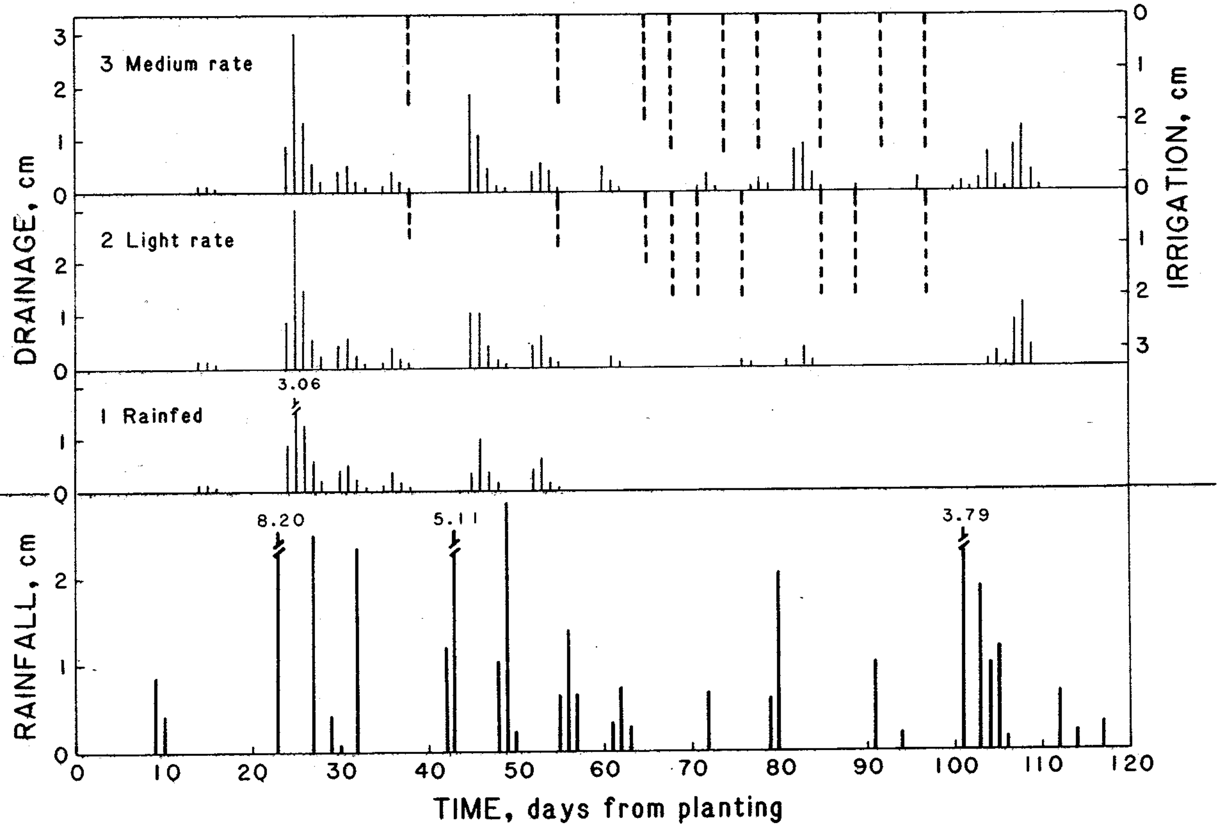

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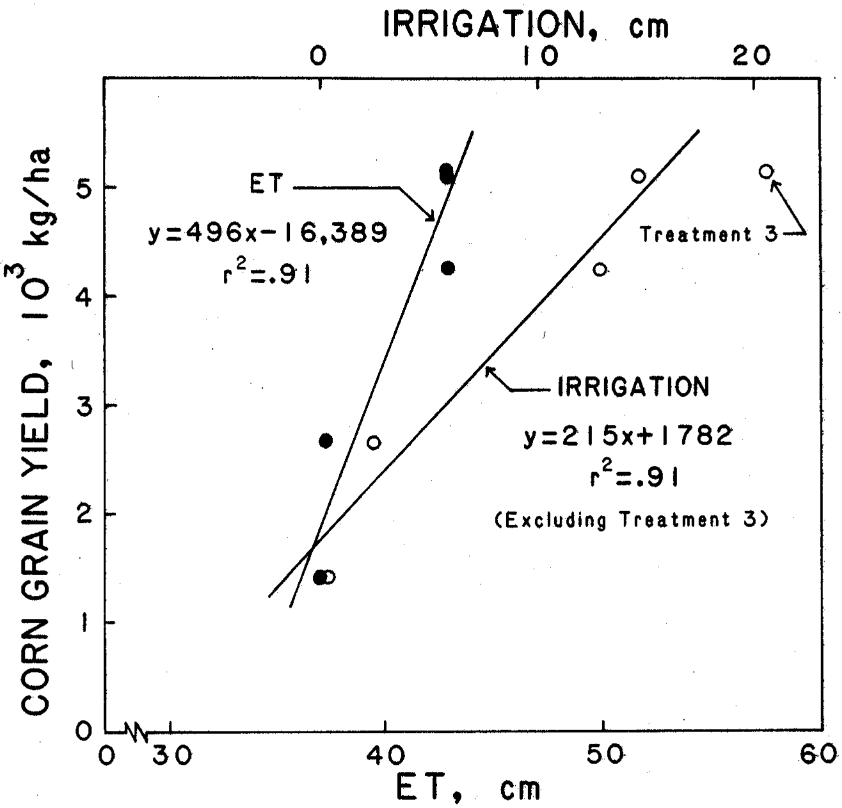

Fig. 2. Grain Yield in Relation to Seasonal Irrigation and Simulated ET, Gainesville, 1979.

The relationships in Fig. 2 are in agreement with theoretical expectations. If all applied water was used as evapotranspiration, the two curves would be superimposed. It does not appear likely that the irrigation function would ever be larger than the ET function. The smaller slope of the irrigation function is an indication of the inefficiency of irrigation management for the particular season. In fact, an estimate of the fraction of applied water which was used as ET is given by the ratio of regression coefficients (21.5/496 = 0.43). Likewise, individual treatment estimates are given by the ratio of the increase in ET and the seasonal irrigation amount (for treatment 3, 6.1/20.6 = 0.30). The latter calculations are more appropriate if, as indicated by Stegman et al. (1980), the irrigation function is typically curvilinear and curves away from the ET function as irrigation depths increase. In 1980 Georgia experiments, an estimated 67% of irrigation was used to increase ET. A comparable value of 70% was obtained in Florida in 1980 from irrigation and ET production functions of 350 and 500 kg/ha-cm, respectively. Because of rainfall uncertainty in the southeastern U.S., it is not possible to avoid an appreciable loss of irrigation water by deep percolation.

Production functions like those in Fig. 2 are useful in several ways. First, the general relationship of crop yield to irrigation must be determined through experience and research in order to develop economical water management systems and practices for particular soil-climate-crop systems. The researcher investigates the processes affecting the relationship and tests experimental systems and practices against the historical data base. The farmer develops management strategies to achieve what has been shown to be possible and more. Policymakers and planners need the above information in developing and allocating resources. For humid conditions, it appears that the linear portion of the irrigation function should be the working basis for irrigation scheduling strategies. The goal should be to achieve the yield potential associated with maximum ET while minimizing non-ET losses of applied water. As others have shown (Phene and Beale 1976, Rawlins and Raats 1975, Skogerboe et al 1979, and Stegman et al. 1980) and as the data in Table 2 and Fig. 2 show, relative to treatment 3, irrigation must be scheduled frequently and at rates which leave some unfilled soil storage for following rainfall. Non-ET losses of water may interact with the crop and soil to cause yield reductions through leaching of nutrients and poor soil aeration (Campbell and Phene 1977, Campbell and Moreau 1979, and Skogerboe et al. 1979).

The ET function can be a family of curves depending on the sequencing of ET deficits during the growing season (Stegman et al. 1980). The latter also affects the scatter of data points for the irrigation function. However, a mean ET function based on near optimum ET deficit sequencing is a valuable function. It represents a goal and a standard against which strategy results can be tested. Moreover, this function as well as others in the family of functions predicts the yield reduction for given ET deficits.

Water management implications of these two types of functions have been discussed in detail by Stegman et al. (1980). It is encouraging that recent results of water management studies conducted in the humid southeastern U.S. parallel the more extensive data from subhumid and semiarid regions and can be subjected to similar analysis and evaluation. Differences in water management goals and strategies between these regions should, in the main, reflect differences in available water resources and rainfall uncertainties.

Additional water management strategy considerations will be mentioned only briefly. Strategies related to fractional replenishment of the depleted soil profile and deficit irrigation cannot be isolated from the question of irrigation timing. A strategy of variable timing throughout the crop season would be expected to be most appropriate to the temporal changes in canopy coverage, plant rooting depth, and plant growth stage-related sensitivity to water stress. Timing may be based on the plant condition (water potential, observable wilting, etc.), soil condition (water potential, water content, and water depletion level and distribution in the root zone), and estimated ET (from pan evaporation or from real time of historical meteorological data, solar radiation, vapor pressure, wind speed, and temperature). Crop condition is the basic consideration since the goal is to supply the water needs of the plant for maximum photosynthesis. In the absence of measurements of crop and soil conditions, observation of indicator plants (weeds, sensitive varieties or cultivars) or indicator areas in the field can be helpful in determining when to irrigate.

Adapting the cropping pattern and sequence to irrigation farming is another aspect of management strategy. High capital and operating costs of irrigation equipment may require changes such as multiple cropping--a practice currently being recommended in Georgia as a means of reducing the risk of irrigation farming.

System design impacts vary strongly on irrigation strategies directed toward the goal of full ET for the plant canopy and no drainage of water below the root zone. A high degree of application uniformity is a necessity. Thus, irrigation may need to be scheduled at night when wind is less of a factor. Although many systems are large (100 ha or more), smaller center-pivot systems (20 ha or less) are becoming more common throughout the southeastern

U.S. due to small field size and rolling topography. These smaller systems may require 24 hours or less per revolution while large systems may require 48 hours or more. Both are usually designed to replace an expected accumulated ET depth during a revolution. Frequently, the speed (and thus, output) can be varied to meet variable ET demands and permit short shut-down periods between revolutions. A system not able to meet ET demand during the designed revolution time forces a deficit irrigation practice which will not supply water needs during an extended drought. For the March-June period in South Georgia, Sheridan et al. (1979) have found that in one out of 2 years there will be at least 21 consecutive days with less than 0.6 cm of rainfall on any day. Attempts to minimize underdesigned system problems by beginning irrigation ahead of need results in water loss during rainfall intervals and water stress damage during long droughts. Special soil and climate conditions in Nebraska permitted the successful use of high-frequency irrigation at less than ET demand rates (Fischbach and Somerhalder 1974). However, discussions with Cooperative Extension Service personnel and farmers revealed that substantial yield losses were experienced in 1977, 1980, and 1981 in Georgia due to delaying the initial irrigation for 2-3 days and then applying water at ET demand rates during an extended drought. The soil profile initially became so dry that the system simply could not "catch up." Consequently, only the upper portion of the root zone had adequate moisture for the duration of the drought. This is typical of center-pivot irrigation systems (Stegman et al. 1980), and more research data are needed to resolve this particular design and management problem under humid conditions.

CONCLUSIONS

There are two production functions for consideration in developing irrigation strategies and in evaluating the successes or failures of strategies used. The ET function (yield per unit of water used in seasonal ET) should be reasonably constant from season to season and represent a maximum or goal to achieve in irrigation management. Moreover, this function predicts the losses in yield to be expected per unit of seasonal ET deficit. In marked contrast, the irrigation function (yield per unit of irrigation water applied during the season) is highly variable with season and with the irrigation treatments used to find the function. Nevertheless, average irrigation function values (in the linear range) are needed in assessing the economic potential of irrigation farming. Essential elements of irrigation management strategies for humid regions include: variable scheduling practices with stage of growth and crop condition, irrigation to replenish a fraction of the water-depleted profile, irrigation to prevent plant water stress, and the development of an intensive overall crop management scheme attuned to the dynamic soil-plant-climate system.

REFERENCES

1. Bruce, R.R., J.L. Chesness, T.C. Keisling, J.E. Pallas, Jr., D.A. Smittle, J.R. Stansel and A.W. Thomas. 1980. Irrigation of crops in the southeastern United States: Principles and practice. USDA-SEA. ARM-S-9/May 1980. 54 p.

2. Butson, K.D. and G.M. Prine. 1968. Weekly rainfall frequencies in Florida. Florida Ag. Exp. Sta. Circular S-187. April 1968. 41 p.

3. Campbell, R.B. and R.A. Moreau. 1979. Ethylene in a compacted field soil and its effect on growth, tuber quality, and yield of potatoes. Amer. Potato J. 56: 199-210.

4. Campbell, R.B. and C.J. Phene. 1977. Tillage, matric potential, oxygen and millet yield relations in a layered soil. TRANS. of the ASAE 20: 271-275.

5. deWit, C.T. 1958. Transpiration and crop yields. Versl. Landbouwkd. Onderz. 64.4. 88 p.

6. Fischbach, P.E. and B.R. Somerhalder. 1974. Irrigation design requirements for corn. TRANS. of the ASAE 17: 162-165, 171.

7. Hanks, R.J. 1974. Model for predicting plant yield as influenced by water use. Agron. J. 66: 660-664.

8. Jensen, M.E. and H.R. Haise. 1963. Estimating evapotranspiration from solar radiation. J. Irrig. Drain. Div., ASCE 89: 15-41.

9. Morey, R.V., J.R. Gilley, F.G. Bergsrud and L.R. Dirkzwager. 1980. Yield response of corn related to soil moisture. TRANS. of the ASAE 23: 1165-1170.

10. Musick, J.T. and D.A. Dusek. 1980. Irrigated corn yield response to water. TRANS. of the ASAE 23: 92-98, 103.

11. Phene, C.J. and O.W. Beale. 1976. High-frequency irrigation for water management in humid regions. Soil Sci. Soc. Amer. J. 40: 430-436.

12. Rao, P.S.C., J.M. Davidson and L.C. Hammond. 1976. Estimation of nonreactive and reactive solute front locations in soils. In Residual Management by Land Disposal. Proc. Hazardous Waste Residue Symposium. Tucson, AZ. p. 235-242.

13. Rao, P.S.C., J.M. Davidson and R.E. Jessup. 1981. Simulation of nitrogen behavior in the root zone of cropped land areas receiving organic wastes. In Simulation of Nitrogen Behavior in Soil-Plant Systems (edited by M.J. Frissel and J.A. vanVeen). Pudoc, Wageningen, The Netherlands. p. 81-95.

14. Rawlins, S.L. and P.A.C. Raats. 1975. Prospects for high-frequency irrigation. Science. 188: 604-609.

15. Rhoads, F.M. and R.L. Stanley, Jr. 1973. Response of three corn hybrids to low levels of soil moisture tension in the plow layer. Agron. J. 65: 315-318.

16. Robertson, W.K., L.C. Hammond, G.K. Saxena and H.W. Lundy. 1973. Influence of water management through irrigation and a subsurface asphalt layer on seasonal growth and nutrient uptake of corn. Agron. J. 65: 866-868.

17. Sheridan, J.M., W.G. Knisel, Jr., T.K. Woody, III and L.E. Asmussen. 1979. Seasonal variation in rainfall and rainfall-deficient periods in the Southern Coastal Plain and Flatwoods regions of Georgia. Georgia Agr. Exp. Sta. Res. Bull. 243. 73 p.

18. Skogerboe, G.V., J.W.H. Barrett, B.J. Treat and D.B. McWhorter. 1979. Potential effects of irrigation practices on crop yields in Grand Valley. EPA-600/2-79-149. 193 p.

19. Stegman, E.C., J.T. Musick and J.I. Stewart. 1980. Irrigation water management. In Design and operation of farm irrigation systems (edited by M.E. Jensen) ASAE Monograph 3. Amer. Soc. Agric. Eng., St. Joseph, Michigan. p 763-816.

20. Stewart, J.I., R.D. Misra, W.O. Pruitt, and R.M. Hagan. 1975. Irrigating corn and grain sorghum with a deficient water supply. TRANS. of the ASAE 18: 270-280.

21. Tanner, C.B. 1981. Transpiration efficiency of potato. Agron. J. 73: 59-64.

22. van Bavel, C.H.M. and F.J. Verlinden. 1956. Agricultural drought in North Carolina. North Carolina Ag. Exp. Sta. Tech. Bull. 122. June 1956. 60 p.

23. van Bavel, C.H.M. and J.R. Carreker. 1957. Agricultural drought in Georgia. Georgia Ag. Exp. Sta. Tech. Bull. N.S. 15. 41 p.