THE IMPORTANCE OF CROP PRODUCTION FUNCTIONS IN EVALUATING CONSUMPTIVE USE OF WATER

Eldon G. Hanson and Theodore W. Sammis
Professor Emeritus and Assistant Professor
Department of Agricultural Engineering
New Mexico State University

INTRODUCTION

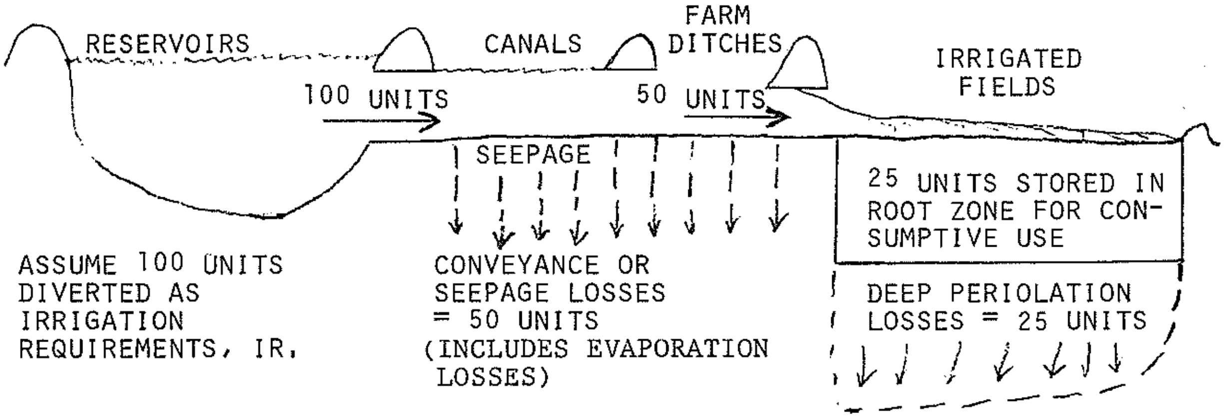
Consumptive use (evapotranspiration) information is required for many purposes, some of which are: (1) planning irrigation projects; (2) determining irrigation requirements for crops for designing irrigation systems; (3) determining equitable water rights; and (4) evaluating the life expectancy of the water supply in underground basins.

Consumptive use as used herein, is synonymous with evapotranspiration (ET) which is the quantity of water transpired by plants, retained in plant tissue, and evaporated from adjacent soil surfaces in a specified time period. It is usually expressed as a depth of water in centimeters, inches, or feet, etc.

Consumptive use is not a fixed value since it varies with crop yield. This variation is shown with crop-production functions which will be discussed later in this paper.

Normal consumptive use is the evapotranspiration that occurs when crops produce average yields. It may be determined by plotting the average yields on crop-production functions.

As an example to illustrate the importance of and the application of consumptive use as a base for computing irrigation requirements, Figure 1 is presented. In the figure and example, the following assumptions are made:



$$\text{IRRIGATION EFFICIENCY} = \frac{\text{25 UNITS STORED IN ROOT ZONE}}{\text{100 UNITS = IR (RESERVOIR DIVERSION)}} = 25\%$$

$$\text{CONVEYANCE EFFICIENCY} = \frac{\text{50 UNITS DELIVERED}}{\text{100 UNITS DIVERTED}} = 50\%$$

$$\text{FIELD APPLICATION EFFICIENCY, Ea} = \frac{\text{25 UNITS STORED}}{\text{50 UNITS APPLIED TO FIELDS}} = 50\%$$

$$\text{IRRIGATION EFFICIENCY} = (E_c = 50\%)\ (E_a = 50\%) = 25\%$$

IRRIGATION REQUIREMENTS, IR, MAY BE COMPUTED IF CONSUMPTIVE USE AND IRRIGATION EFFICIENCY ARE KNOWN THUS:

$$IR = \frac{\text{25 UNITS OF CONSUMPTIVE USE}}{\text{IRRIGATION EFFICIENCY} = 25\%} = \frac{25}{.25} = \text{100 UNITS}$$

Fig. 1. Profile of an irrigation system showing types of water losses and examples of computations of irrigation efficiencies and irrigation requirements.

1. 100 units of water are diverted from the reservoirs
2. 50 units are lost in conveyance by seepage and evaporation
3. 50 units are applied to irrigated fields of which half or 25 units are lost by deep percolation, thus leaving only 25 units as stored moisture in root zone for consumptive use.

The main objective of irrigation is to supply moisture in the root zone for plant growth. With only one-fourth of the diverted water, or only 25 units stored as soil moisture in the figure, the irrigation efficiency is 25%. The irrigation efficiency may also be computed by multiplying the conveyance efficiency, E_c, by the water applications efficiency, E_a, as shown in Figure 1.

Irrigation requirements may be computed with consumptive use as a base by working the example in reverse, if irrigation efficiency is also known thus:

$$\text{Irrigation Requirements} = \frac{\text{Consumptive Use} = 25\text{ units}}{\text{Irrigation Efficiency} = 25\%} = \frac{25}{25} = 100\text{ units}$$

Crop-production functions cited in this paper were obtained from research by Hanson and Sammis (10), Sammis et al. (12), and Horton, Wierenga, and Beese (11). The main objective of this research, which will be discussed in the remainder of this paper, was to determine evapotranspiration (ET) of selected crops throughout the growing season at Artesia, Clovis, Farmington, Las Cruces, and Los Lunas (Fig. 2) and to relate ET data to yield.

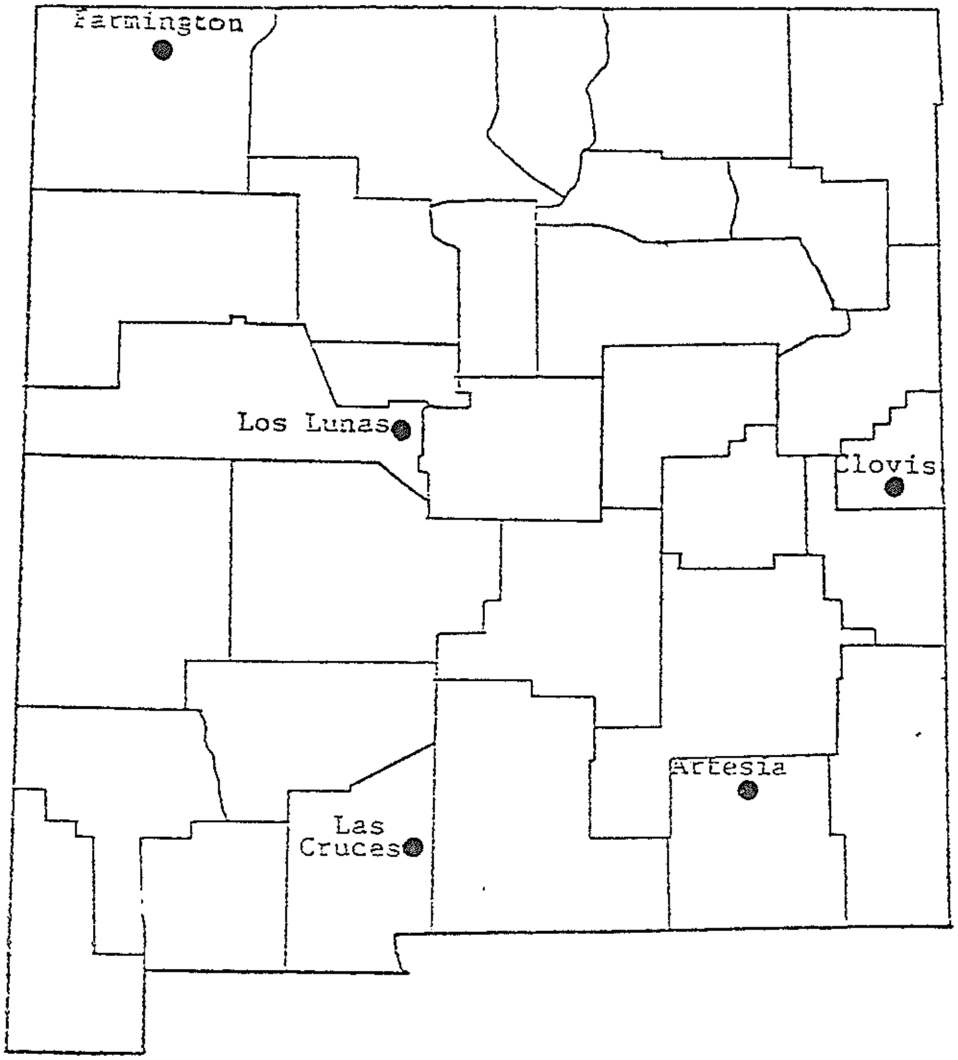


Fig. 2. Locations where evapotranspiration measurements are being conducted on selected crops in New Mexico.

MATERIALS AND METHODS

Figure 3 is a map of the 1976 and 1977 study sites and surrounding fields. Figure 4 is a map of the 1978 research site. Table 1 presents the various crops grown at the study sites throughout the state. For 1976 and 1977 research, the ET rate was measured for each crop with a non-weighing type lysimeter and a water-balance technique.

$$ET = I + R - D \pm \Delta SM \qquad (1)$$

where I = Irrigation

R = Rainfall

D = Drainage

ΔSM = Change in soil moisture

Lysimeters 1.8 x 1.8 meters and 1.21 meters deep were installed in field plots for each crop. Lysimeter construction plans are presented in Figure 5. A hole was dug by hand with the soil moved from the hole and stored according to the order it was removed. The hole was then lined with plywood 1.9 cm thick (3/4 inch) and five layers of 4 mil black plastic. Suction candles and drainage pipe 1.27 cm in diameter (1/2 inch) were installed at the bottom. The lysimeters were filled with 15 cm of sand and then backfilled with the original soil in the order that it was removed. Neutron access tubes were installed in the lysimeters to measure weekly, with a neutron probe, the changes in soil moisture at every 15 cm of depth. The drainage water was pumped out with a vacuum pump during several days following irrigations.

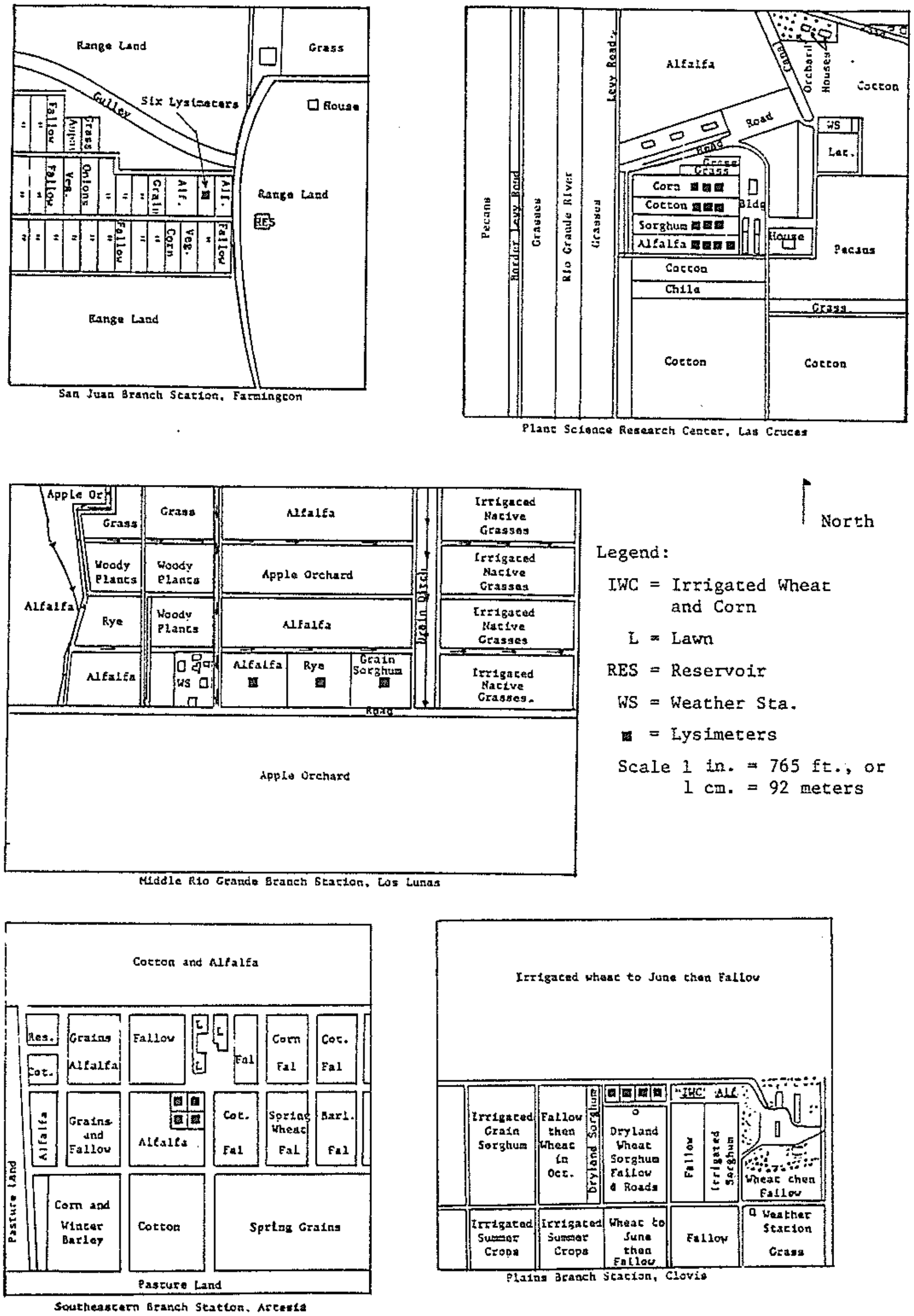


Fig. 3. Study sites and surrounding fields 1976 and 1977.

Table 1. CROPS GROWN AT STATIONS

Location	1976[a]	1977[a]	1978[b]
Las Cruces - Plant Science Research Center	Alfalfa, Mesilla Sorghum, RS671[c] Cotton, 1517V	Alfalfa, Mesilla Sorghum, RS671[c] Cotton, 1517V Barley Sudangrass	Alfalfa, Hairy Peruvian Cotton, 1517-75
Artesia - Southeastern Branch Station	Alfalfa, Mesilla Barley, Penasco Sorghum, RS671 Cotton, 1517V	Alfalfa, Mesilla Barley, Penasco Sorghum, RS671 Cotton, 1517V	
Los Lunas - Middle Rio Grande	Alfalfa, Mesilla Sorghum, RS671 Bluegrass, Newport	Alfalfa, Mesilla Sorghum, RS671 Bluegrass, Newport Rye, TP	
Clovis - Plains Branch Station	Alfalfa, Mesilla Sorghum, DeKalb E59+ Corn, Pfizer TXS-115A Wheat, Centurk	Alfalfa, Mesilla Sorghum, DeKalb E59+ Corn, Pfizer TXS-115A Wheat, Centurk	
Farmington - San Juan Branch Station	Alfalfa, Mesilla Sorghum, RS671 Barley, Steptoe Corn, PX610	Alfalfa, Mesilla Sorghum, RS671 Barley, Steptoe Corn, PX74	

[a] Crops grown in lysimeters with surface flooding.
[b] Crops grown in field plots with sprinkler irrigation.
[c] Crop yields were omitted due to damage by birds.

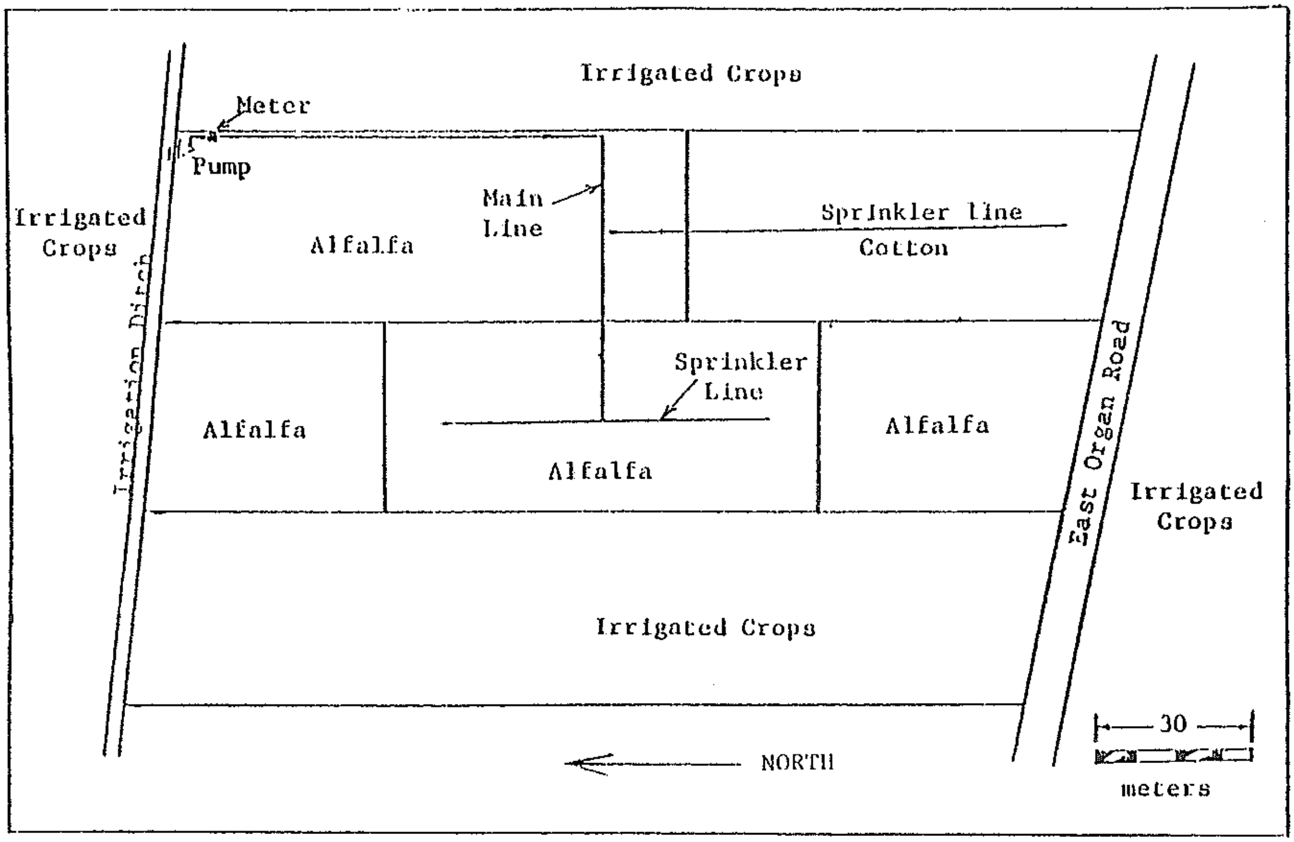
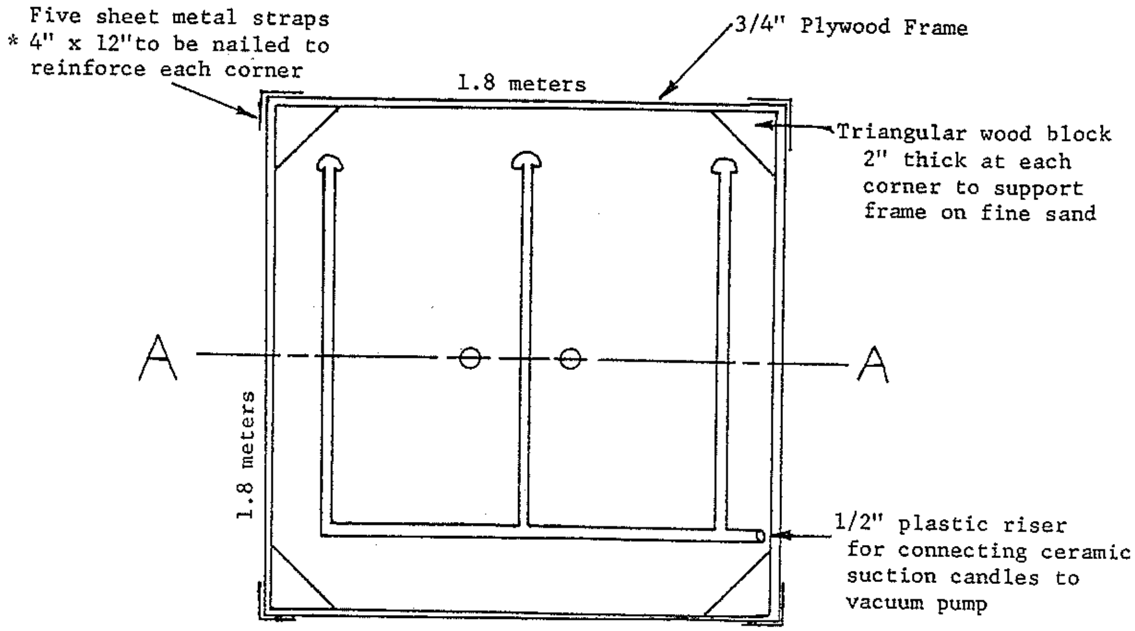


Fig. 4. Schematic diagram of the alfalfa and cotton plots irrigated by sprinklers. 1978.



PLAN

*1 inch = 2.54 cm

PROFILE CROSS-SECTION A-A

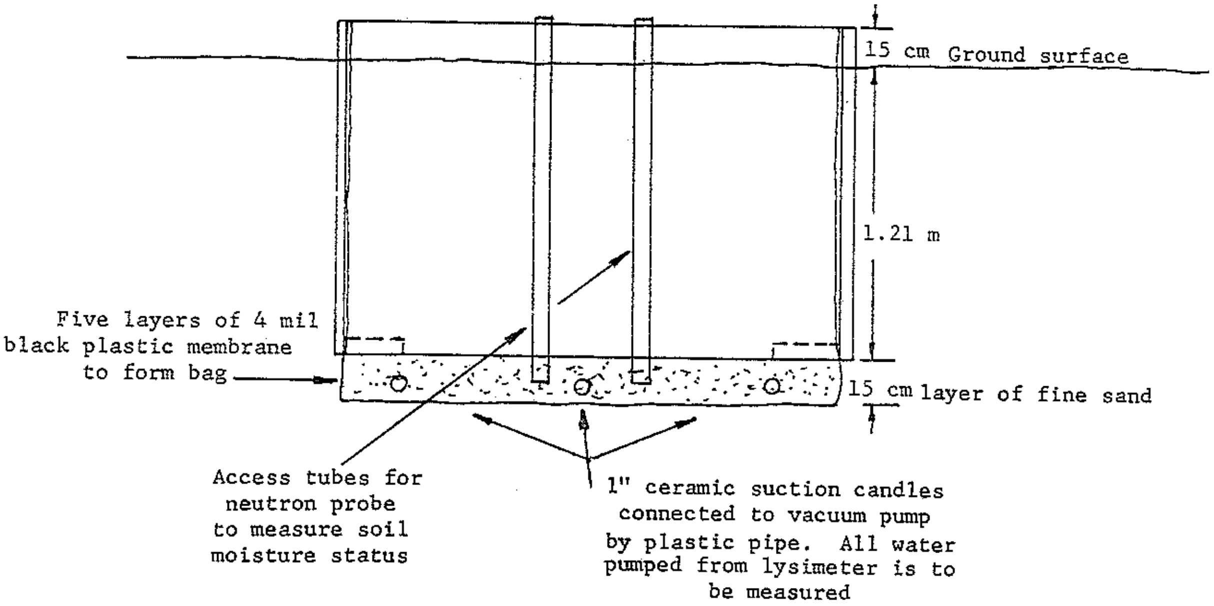


Fig. 5. Plan and profile of drainage-type lysimeters.

Irrigations were generally applied weekly during peak evapotranspiration months to assure that crop growth and yields would not be limited by inadequate water. Fertilizer was applied as necessary so that deficiencies would not limit growth and evapotranspiration rates.

Yield was measured from the lysimeters and adjacent field at harvest time.

The 1978 research site (Fig. 4) was located 5 kilometers east of the Plant Science Research Center near Las Cruces. Alfalfa and cotton were each grown in approximately 30- by 50-meter plots using a sprinkler-line source (8) without stressing the crop near the sprinkler-line throughout the growing season. A decreasing total water application was applied away from the line (Figs. 6 and 7). Water quality ranged from 0.43 to 1.61 mmhos per cm (EC x 10^{-3}).

Measurements of soil moisture were taken on the cotton and alfalfa plots at two-week intervals through the growing season. Water applied to the plots was measured with catchment cans spaced every meter away from the sprinkler-line source. The cans were raised in height as the plants grew so their level was the same as the canopy level.

RESULTS AND DISCUSSION

Crop-production functions

Evapotranspiration and yields from lysimeters in 1976 and 1977 have been plotted in Figures 8 through 11. Data from sprinkler plots in 1978 have been plotted in Figures 8 and 9. Also included

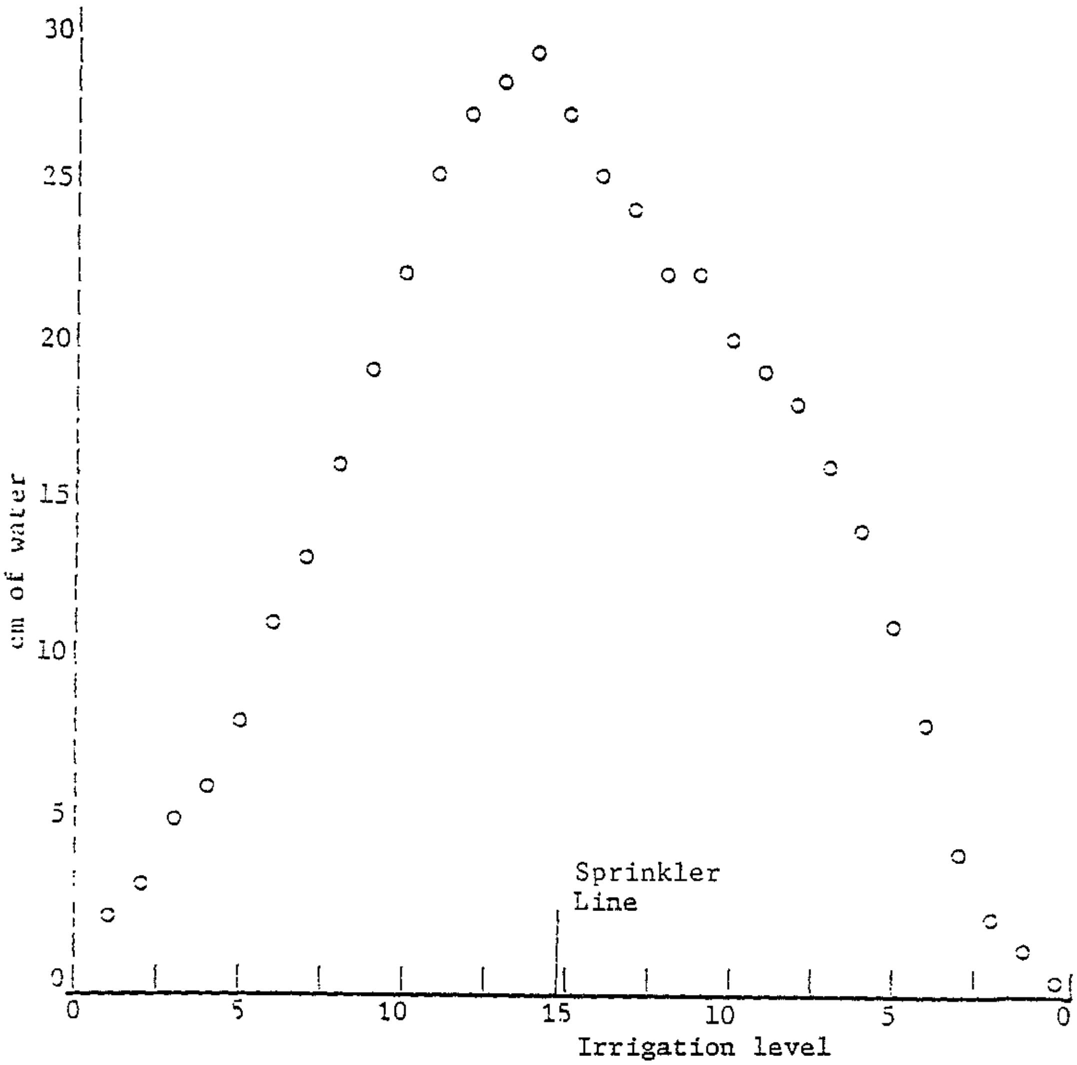


Fig. 6. Total seasonal applied water to the cotton plot (1978) using a sprinkler-line source excluding 16.9 cm (6.7 in.) of rainfall.

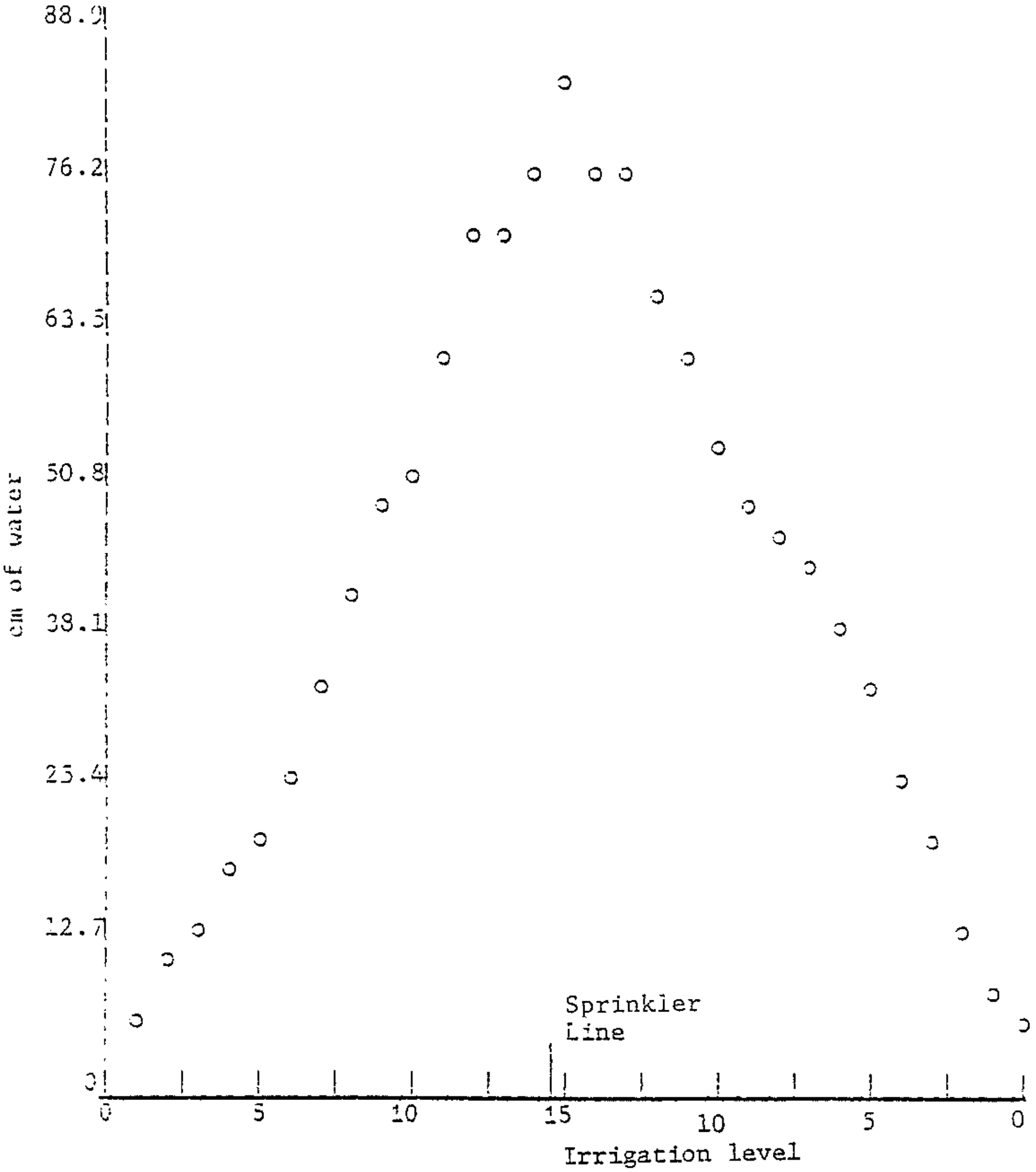


Fig. 7. Total seasonal applied water to the alfalfa plot (1978) using a sprinkler-line source excluding 18 cm (7 in.) of rainfall.

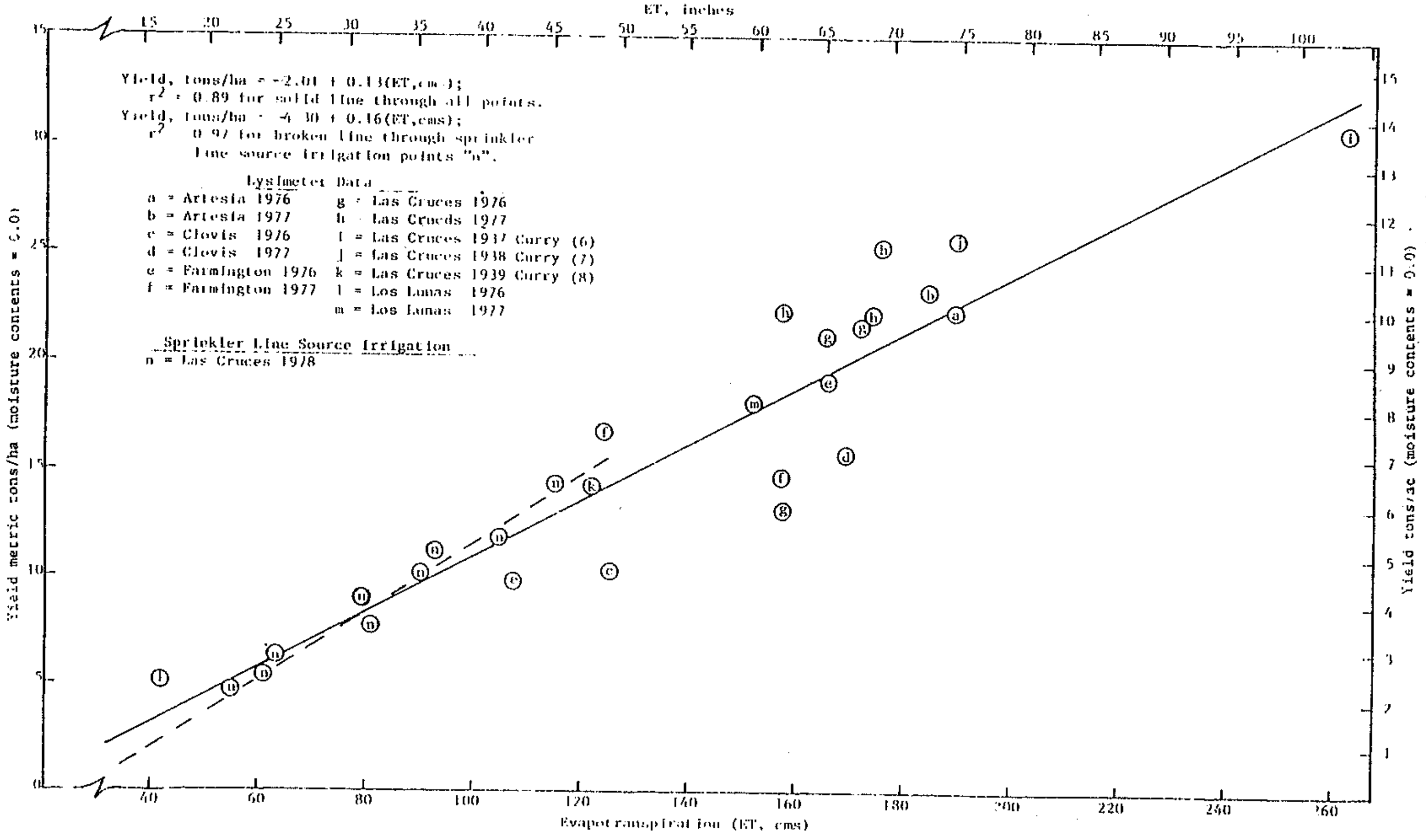


Fig. 8. Crop-production function for alfalfa.

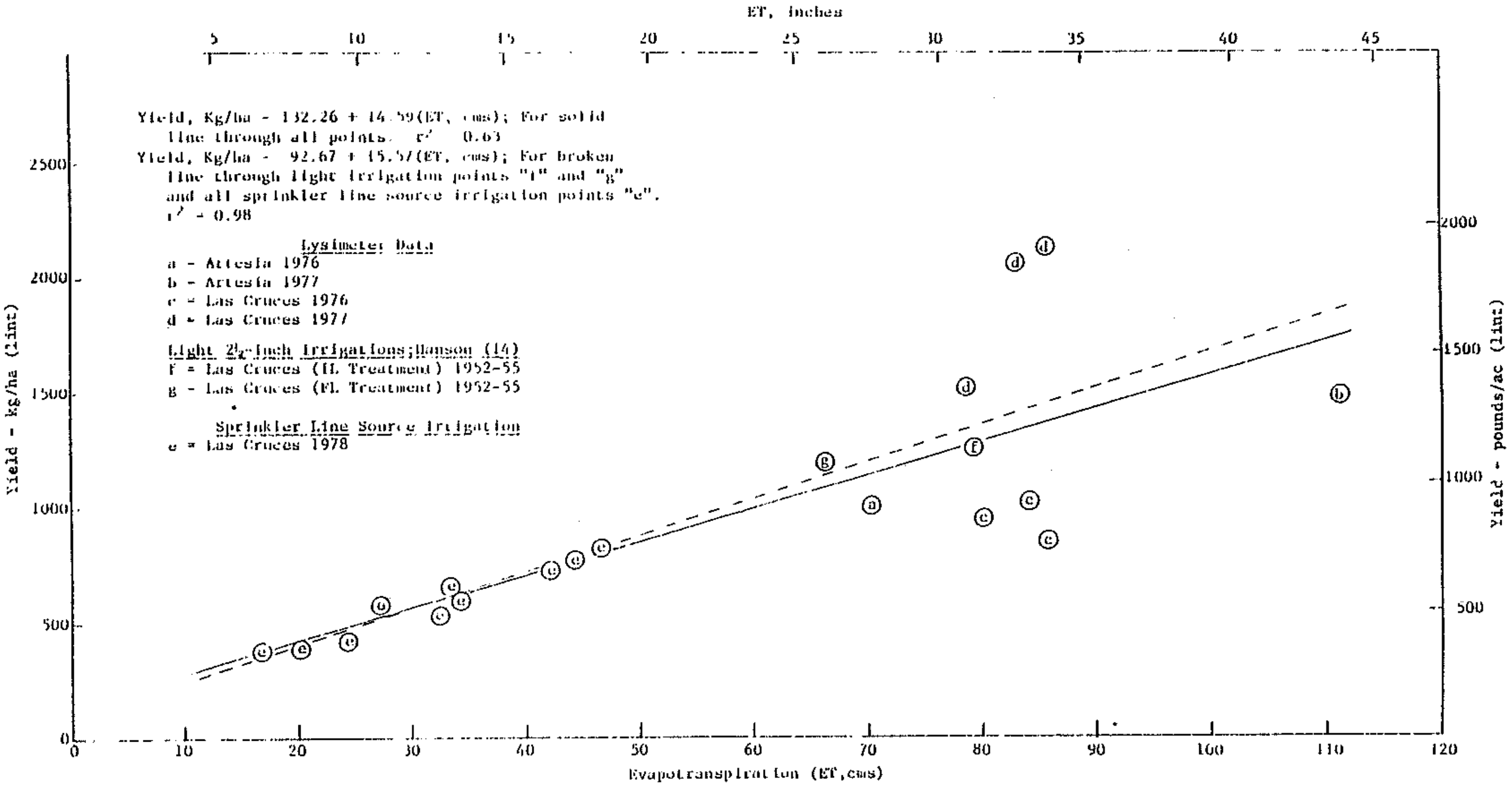


Fig. 9. Crop-production function for cotton.

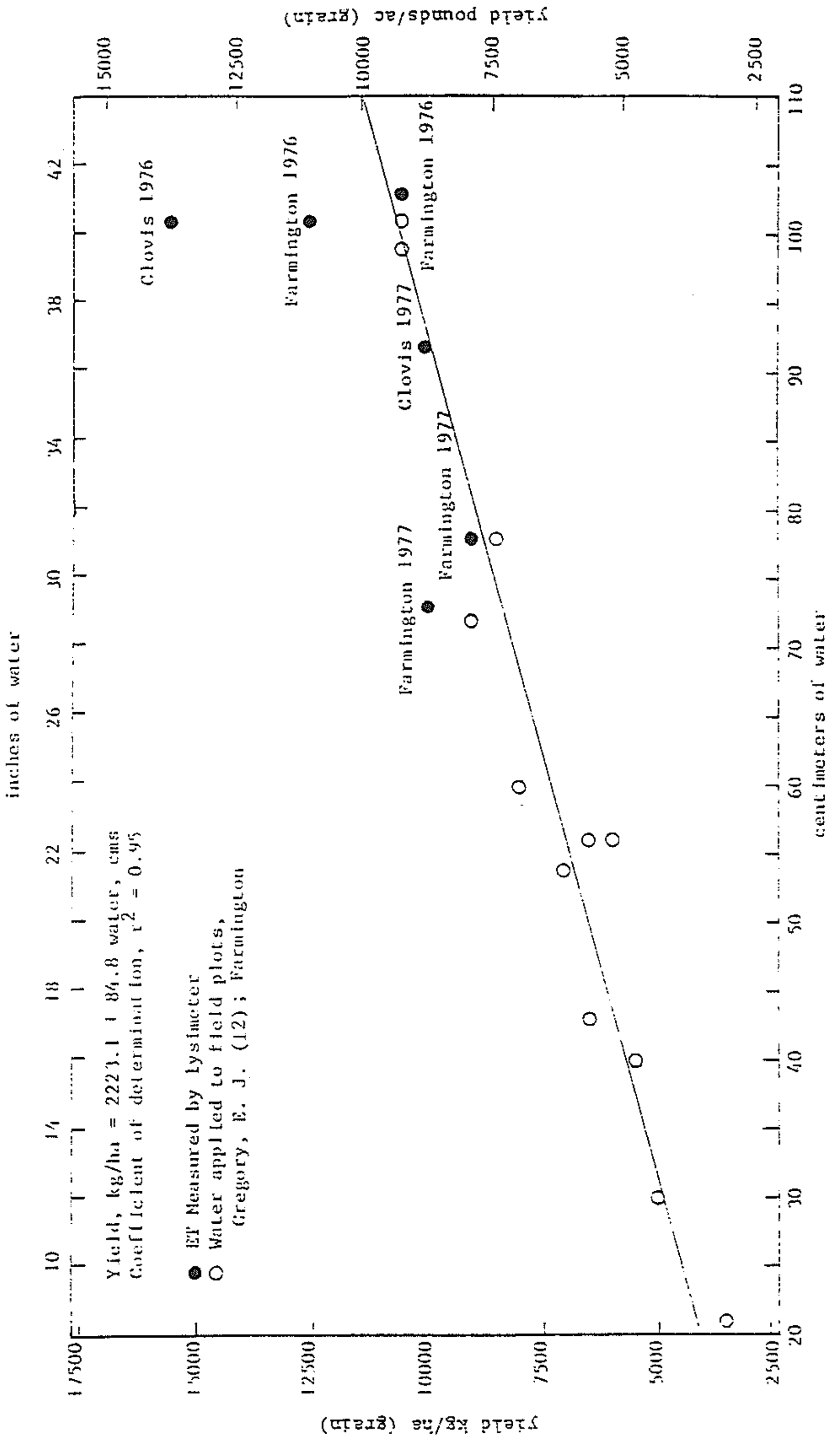


Fig. 10. Crop-production function for grain corn.

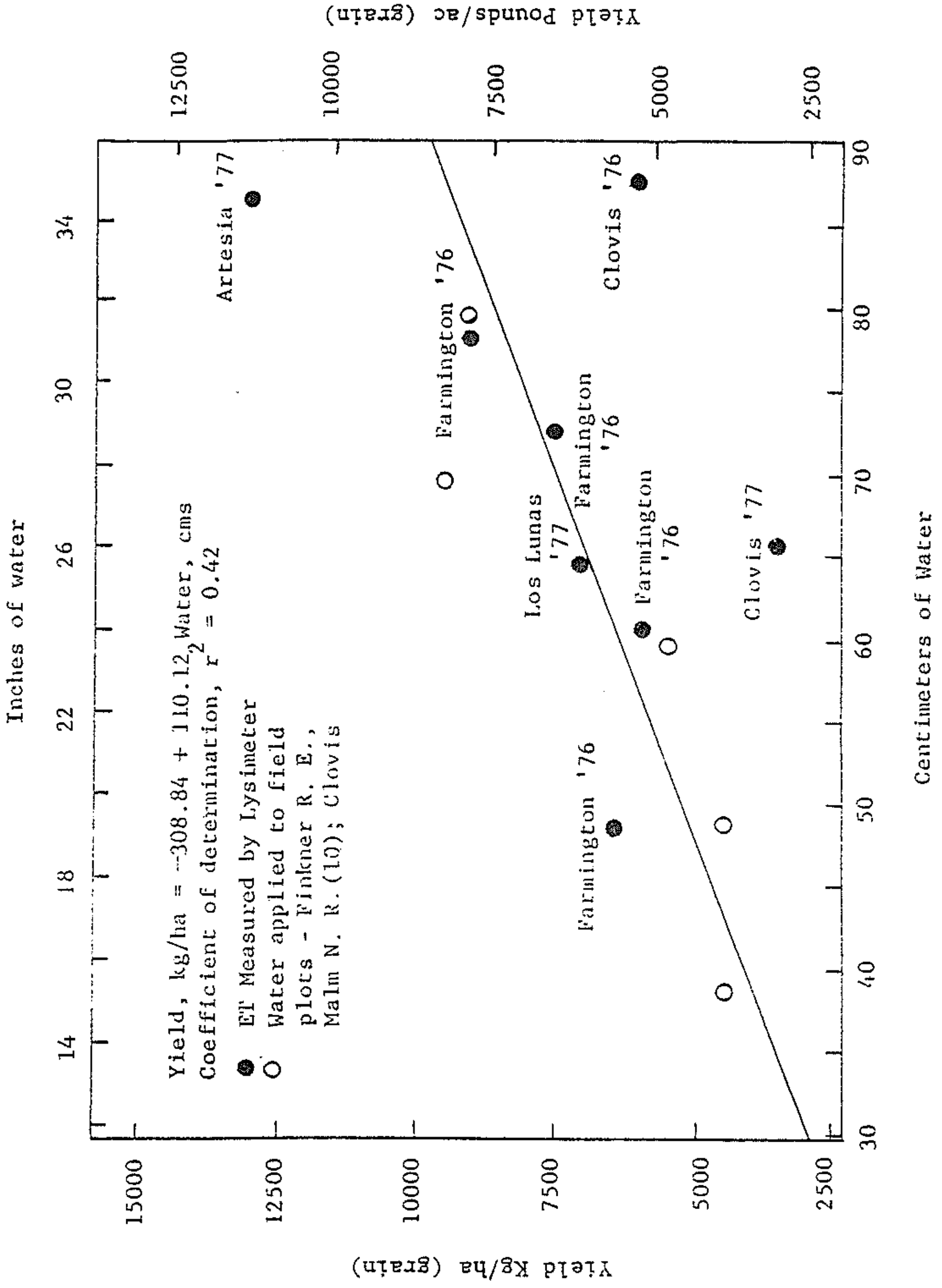


Fig. 11. Crop-production function for grain sorghum.

in Figures 9, 10, and 11 are additional data of water applied and yield from selected irrigation research projects in the state which were conducted earlier by Gregory (7), Finkner and Malm (6), and Hanson and Knisel (9). The crop-production functions are quite linear, as shown with coefficients of determination in Figures 8 through 11. Although the "water applied" measurements of earlier irrigation research projects may not be strictly ET, they are close estimates inasmuch as they represent irrigation treatments of reasonable light irrigations where deep drainage was minimal. The "centimeters of water" in the figures include rainfall.

Crop-production functions from other research by Horton, Wierenga, and Beese (11) with chile in 1977 to 1979 are shown in Figures 12 and 13. The data for each year almost fits a straight line with slopes varying somewhat from year to year. The average r^2 value for three years is 0.84 and 0.80 for green chile and red chile, respectively.

For alfalfa (Fig. 8) and cotton (Fig. 9), the sprinkler-line source data are combined with lysimeter data. The crop-production function for alfalfa, using only the sprinkler-line source data, has a coefficient of determination of 0.97 as a linear function. When the sprinkler-line source data are combined with the lysimeter data, the coefficient of determination is 0.89. In the range of normal production on farms, the results from both curves will not vary more than 6%. Using all of the points is considered to give the best results for alfalfa crop-production functions for the whole state.

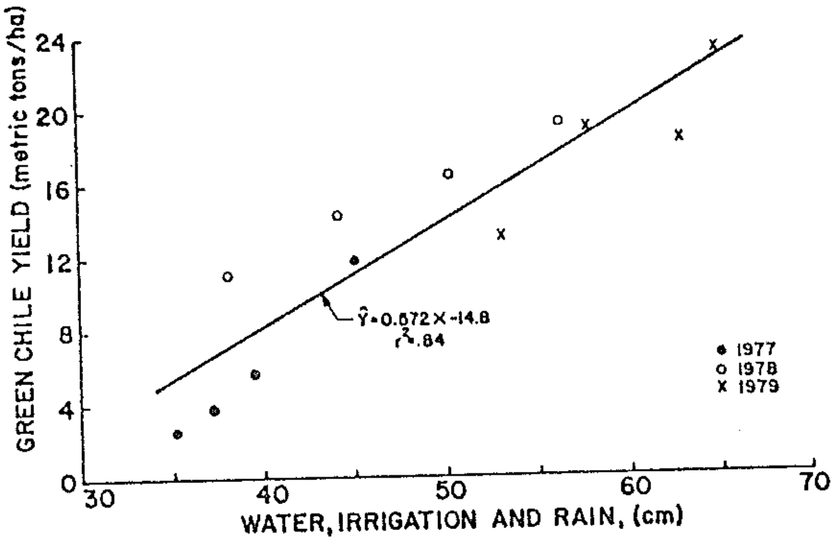


Fig. 12. Average green chile yields (metric tons/ha) by treatment for 1977, 1978 and 1979 versus total water, rain plus irrigation (cm). From Horton, Wierenga, and Beese (11).

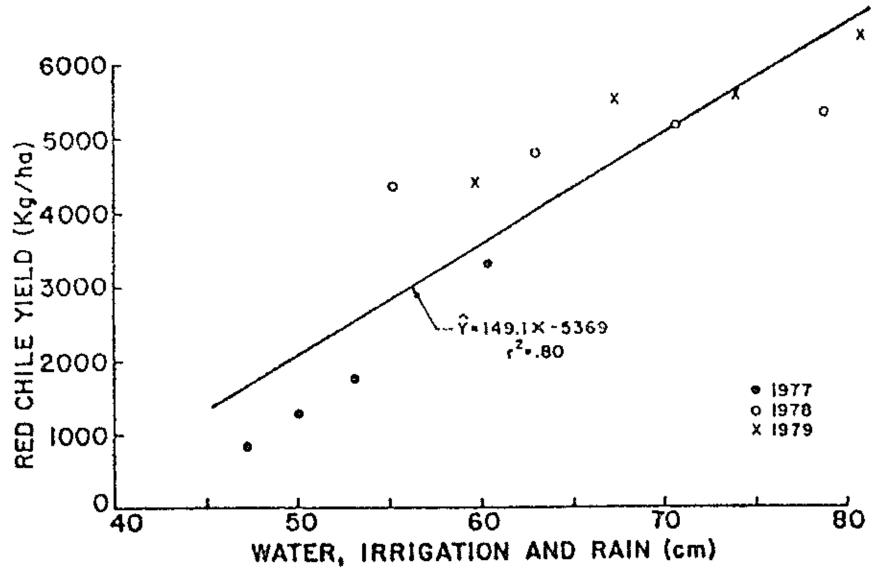


Fig. 13. Average red chile yields (kg/ha) by treatment for 1977, 1978 and 1979 versus total water, rain plus irrigation, (cm). From Horton, Wierenga, and Beese (11).

Sprinkler-line source data are on the low end of the crop-production functions and none of the water applied appears to have been lost by deep percolation. Even the highest sprinkler applications, which were measured near the line, are close to or above the production functions in Figures 8 and 9. If there had been appreciable deep percolation, the points for the higher sprinkler applications would have deviated to the right and to a position below the crop-production function.

The cotton data, using the sprinkler-line source, have a coefficient of determination of 0.98 as a linear function, but when included with lysimeter data, which have considerable scatter, the coefficient of determination drops to 0.63. Again, as with alfalfa, the slope of a curve through the sprinkler-line source data is very similar to the slope of a curve through all the combined points. Even though the cotton-production function for only the sprinkler-line source data has the highest coefficient of determination, the function for all points in the figure is considered to be most appropriate for use. In the range of normal production on farms, the results from both curves will not vary more than 4%.

For the crop-production function for corn in Figure 10, data from an applied water study by Gregory (7) was plotted with lysimeter data. The data are fairly close to the function except for one of the lysimeters in 1976 which is considerable higher in yield than predicted by the crop-production function.

Data in Figure 11 for sorghum has the lowest correlation and additional studies need to be made before any large amount of confidence can be put on the crop-production function in Figure 11. As linear crop-production functions for corn and sorghum, the coefficients of determination are 0.95 and 0.42, respectively.

Stewart et al. (13) report that the crop-production function is linear for grain corn and dry matter with r^2 ranging from 0.51 to 0.98.

It should be noted that the crop-production functions for alfalfa, cotton, grain sorghum, and corn represent studies at more than one location within the state. It appears that as an initial estimate, the crop-production function for alfalfa can be used in several areas of the state. For the other crops, additional studies need to be done in other areas to determine the reliability of transferring the crop-production functions around the state.

Any variable that causes a reduction in evapotranspiration may result in a corresponding reduction in yield. Evapotranspiration reductions may be due to limitations of water, solar radiation, temperature, management, insect infestations, or an increase in soil salinity. Salinity effects may be observed in Curry's data of 1937, 1938, and 1939 (3, 4, 5). These data, shown in Figure 8, were collected using lysimeters that were operated by Curry to maintain a water table at approximately 90 cm (36 inches) below the ground surface. An increase in salt in the soil profile from one year to the next is inevitable with this type of lysimeter. Although there were no measurements of the amount of salt increase, approximate computations indicate that soil salt could have increased as much as 0.4%. This could have caused the yields and evapotranspiration to decrease during 1938 and 1939.

Limitations in Estimating Consumptive Use by the Crop-Production Functions

It is much easier to farm small lysimeters and small experimental plots to obtain high yields than to farm large acreages. Higher yields and higher ET may occur in lysimeters where the soil has been excavated and replaced during the lysimeter construction. This, in effect, is "deep plowing" which will break up impermeable layers or plow pans which may exist in the fields and restrict root growth. The lysimeters used in this research had a 15 cm (6 inch) ridge projecting above the ground to keep out water during furrow or flood irrigations of adjacent fields. The ridge provided somewhat of a shelter and extra advective energy, thus causing some "hothouse" effects. The results of these effects were observed in some lysimeters where the plants within the lysimeters grew faster and larger and required more frequent irrigation to prevent wilting, as compared to crops on adjacent farmland resulting in higher ET.

With respect to crop-production functions, the advective energy and deep plowing effects probably do not distort the ET-yield relationship. Where these factors cause higher ET there also appears to be an overall corresponding increase in yield, thus keeping the slope of the functions quite constant.

In managing small alfalfa plots, for example, harvesting can be accomplished in one day and irrigation water applied the next day. With large-scale farm operations, it may require a week or 10 days to remove the harvested bales before the next irrigation water may be applied. Delaying the irrigation after alfalfa cuttings may restrict ET and alfalfa yield in many types of soils.

Research on experimental plots may show potentials which will be achieved if it is possible to overcome large-area management problems. Economics of large-scale farming place a limit on achieving potential yields with present equipment and costs.

There appears to be more direct and stable correlation between ET and yield of alfalfa than for grain crops. With alfalfa, the entire plant is harvested which gives a better measure of yield than a seed crop for relating yield to ET. With grain crops, there may be a low yield of grain due to weather conditions, cultural practices, or damage by birds or insects, even though the plants may be large and may require a relatively high ET. Consequently, using average county yields (1) of grain crops to compute average county ET using the crop-production function may be misleading. One approach would be to use the yields from fields having relatively high yields for that county. This would represent the ET for the crop under proper management conditions.

Caution must be taken when using the crop-production functions to make sure that the yield published in agricultural statistics represents the total yield. Where some of the alfalfa may have been grazed by animals, the yield published in statistics will be low.

The use of crop-production functions having high coefficients of determination appears to be one of the better methods of estimating ET in an area, provided reasonable estimates of yields can be determined for that area.

The results of this research show that more work is needed with these and other crops, especially with seed crops, to have data with adequate coefficients of determination.

In the past, ET has been estimated with equations based on limited meteorological data, such as the Blaney-Criddle method (2). Results of the Blaney-Criddle method for alfalfa are shown in Figure 14. Using county yields (1) with the crop-production functions results in ET estimates slightly lower than the Blaney-Criddle method. The high ET, shown in the figure for lysimeters, is representative of the high yields measured for alfalfa in the lysimeters (Fig. 8).

In Figure 14, where the average county yield of 5 tons per acre is plotted with the crop-production function, the normal consumptive use is approximately 91 cms or 36 inches. Where reliable crop-production estimates are available for an area, the use of the crop-production function appears to be the best method for determining normal consumptive use.

SUMMARY AND CONCLUSIONS

Alfalfa, grain corn, cotton, chile, and grain sorghum were grown at selected locations throughout the state of New Mexico, including Las Cruces, Artesia, Los Lunas, Clovis, and Farmington.

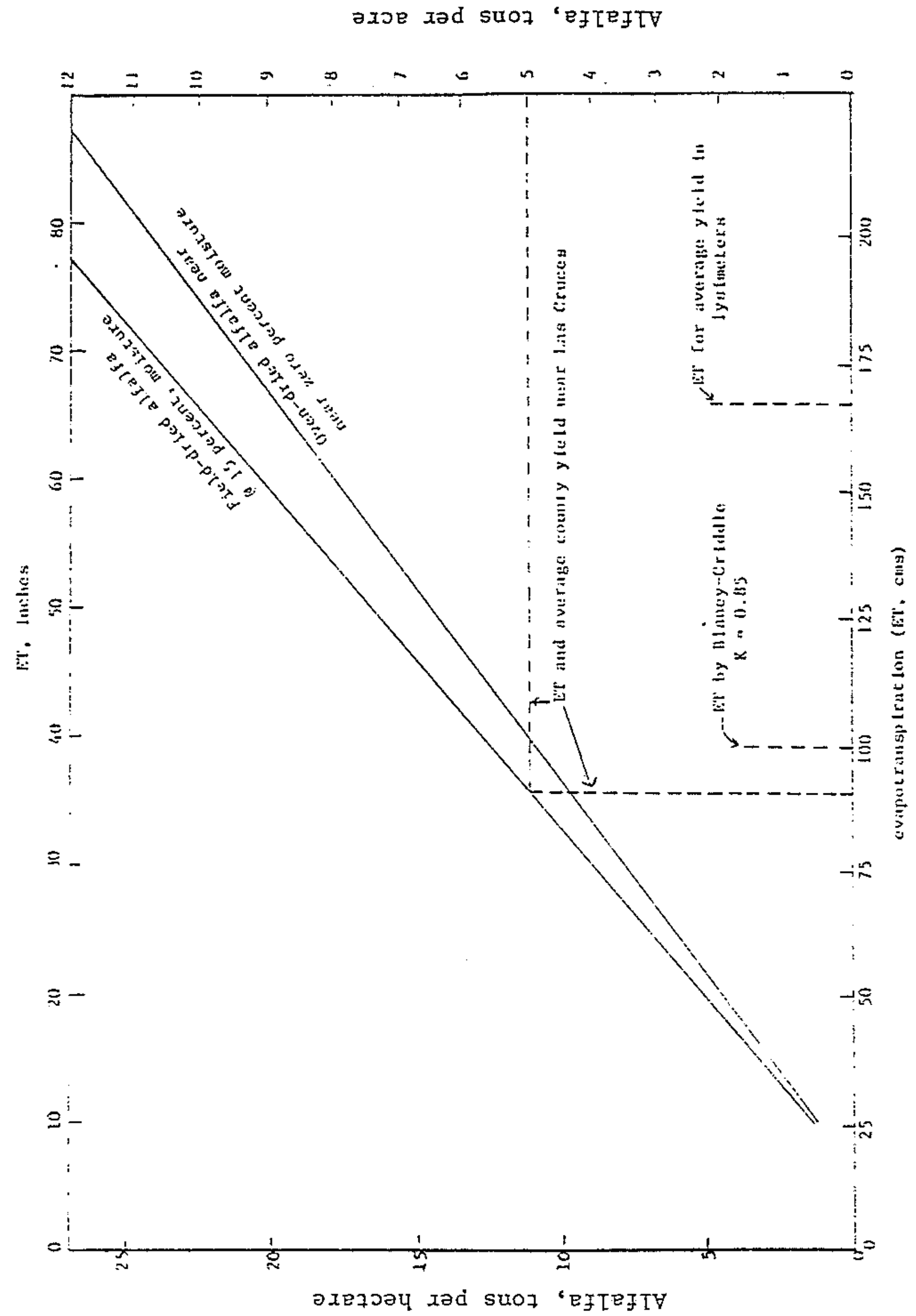


Fig. 14. Crop-production function for alfalfa showing the average evapotranspiration measured in lysimeters at Las Cruces as compared to that of the average county yield and the Blaney-Criddle method.

Lysimeters were installed in the center of the fields, and yields with monthly and yearly evapotranspiration rates were measured in 1976 and 1977. In 1978, a sprinkler-line source was used to irrigate alfalfa and cotton in field plots for the measurement of yields and evapotranspiration. These data and data from other irrigation projects were used to derive crop-production functions for alfalfa, grain corn, cotton, and grain sorghum. Additional data are needed to establish or refine the crop-production functions for most of the crops. The coefficient of determination, r^2, ranged from 0.97 for alfalfa to 0.42 for grain sorghum.

An example of using a crop-production function with average county yield to determine normal consumptive use is presented. Caution must be taken in using county average yields with the crop-production function of grain crops, due to the high variability in county yields. Also, in areas where alfalfa is grazed, part of the yield will not be included in agricultural statistics for use with the crop-production function.

References

1. Anonymous. 1977. New Mexico Agricultural Statistics. New Mexico Department of Agriculture, New Mexico State University. 8 vols., 1962-77.
2. Blaney, H. F., and Criddle, W. D. 1961. Determining consumptive use and irrigation water requirements. U.S. Department of Agriculture, Agricultural Research Service, and Utah State Engineer, July.
3. Curry, A. S. 1937. Consumptive use of water by alfalfa. New Mexico College of Agriculture and Mechanic Arts and Agricultural Experiment Station. Press Bulletin 849.
4. Curry, A. S. 1938. Consumptive use of water by alfalfa in tanks. New Mexico College of Agriculture and Mechanic Arts and Agricultural Experiment Station. Press Bulletin 871.
5. Curry, A. S. 1939. Use of water by alfalfa. New Mexico College of Agriculture and Mechanic Arts and Agricultural Experiment Station. Press Bulletin 904.
6. Finkner, R. E., and Malm, N. R. 1971. Grain sorghum row spacing, plant population, and irrigation studies on the high plains of eastern New Mexico. New Mexico Agric. Expt. Station Bull. 578.
7. Gregory, E. J. 1975. In Annual Report, New Mexico Agric. Expt. Sta., San Juan Branch, Farmington, New Mexico.
8. Hanks, R. J., Keller, J., Rasmussen, V. P., and Wilson, G. D. 1976. Line source sprinkler for continuous variable irrigation-crop production studies. Soil Sci. Am. J. 40.

9. Hanson, E. G., and Knisel, W. G. 1964. Influence of irrigation practices on cotton production and fiber properties. New Mexico Agric. Expt. Sta. Bull. 483.

10. Hanson, E. G., and Sammis, T. W. 1979. Crop production functions for alfalfa, cotton, grain corn, and grain sorghum. In Proceedings of the Inter-American Conference on Salinity and Water Management Technology, Texas A&M University Research Center, El Paso, Texas.

11. Horton, R., Wierenga, P. J., and Beese, F. 1979. Water use of chili peppers. In Proceedings of the Inter-American Conference on Salinity and Water Management Technology, Texas A&M University Research Center, El Paso, Texas.

12. Sammis, T. W., et al. 1979. Consumptive use and yields of crops in New Mexico. New Mexico Water Resources Research Institute Technical Report 115, New Mexico State University, Las Cruces, New Mexico.

13. Stewart, J. I., et al. 1977. Optimizing crop production through control of water and salinity levels in the soil. Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah.