Development and Evaluation of Evapotranspiration Models for Irrigation Scheduling

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ABSTRACT

EVAPOTRANSPIRATION (ET) data for irrigated crops in southern Idaho were used to develop relationships for estimating net radiation and potential ET for the USDA-ARS Computerized Irrigation Scheduling Program. ET estimated with the initial relationships compared well with recent measurements obtained with two sensitive weighing lysimeters. The average daily measured Et for alfalfa for 128 days when there was full cover was 7.23 mm, while the average daily estimated ET was 7.15 mm.

Crop curve relationships were developed from the ET results for snap beans (*Phaseolus vulgaris* L). The depletion of soil water was predicted for two years of irrigated beans with the scheduling program using the improved crop curves and compared with the measured as a test of its performance. The standard deviation of the difference between predicted and measured was about 0.95 mm/day from planting until harvest. The results also demonstrated the importance of obtaining representative meteorological data for irrigation scheduling.

INTRODUCTION

Several years of daily evapotranspiration (ET) data for irrigated crops, obtained with two precision weighing lysimeters, and meteorological and energy balance data were used to develop and evaluate an ET model for irrigation scheduling. The model first estimates maximum or potential ET (E_{tp}) for a reference crop as a function of meteorological conditions. Then the model estimates daily ET for a given crop according to stage of growth with a crop curve function that relates ET to E_{tp}. The model adjustes for increased evaporation when the soil surface is moist.

ET is a primary component of the water balance of a cropped field. Water depleted from the soil by ET must be replenished in arid regions by irrigation for successful crop production. Direct measurement of ET is difficult and costly; therefore the objective of the research program of which this study was a part is to develop models to estimate ET from more easily obtainable data.

A computerized irrigation scheduling program developed by Jensen, Wright, and Pratt (1971), commonly referred to as the USDA-ARS Irrigation Scheduling Program, provides estimates of the timing and amount of irrigation water needed using weather data and relatively simple data on the crop and soil situation. With this program, a reference potential ET is computed with a modified Penman (1963) combination equation described by Wright and Jensen (1972), who used lysimeter and energy balance data to adjust the coefficients of the aerodynamic term for arid irrigated areas. Crop curves used in the original scheduling program were based upon available consumptive use data, most of which were obtained with gravimetric soil sampling procedures over many years. The irrigation scheduling program with its applications has been summarized, along with supporting information on the consumptive use of water and irrigation water requirements (Jensen, 1974). The original program used the best procedures available at the time and satisfied many of the needs for irrigation scheduling. It was fully anticipated that improvements would be added as needs changed and further developments became available.

The ET-estimating procedures were evaluated in this study using recent measurements obtained with two weighing lysimeters. The present larger data base of accurate ET measurements permits developing improved crop curves. An improved crop curve for beans (*Phaseolus vulgaris* L (cultivar slimgreen)) is discussed. This curve should improve the accuracy of the scheduling program in predicting depletion of soil water by most irrigated snap and dry edible bean crops.

PROCEDURES

Daily ET measurements have been obtained with a precision lysimeter at Kimberly, ID since 1968. In 1971, a second lysimeter was installed in an adjacent field. This permitted the simultaneous measurement and comparison of ET from two crops, with one serving as a reference to the other. These lysimeters, similar to those described by Ritchie and Burnett (1968), are 1.83 m square by 1.22 m deep. At installation, the soil was excavated and placed in the lysimeters by soil layers and packed to the original bulk density. Each lysimeter is supported on a mechanical floor stand scale with a counter balance. The net weight, representing essentially the water content of the soil, is sensed with an electronic load cell. Weight differences provide a direct measure of ET with an accuracy better than 0.1 mm/day. Each lysimeter is installed in a field of approximately 2.8 ha to provide adequate fetch. Alfalfa was used as the reference crop for maxi-

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mum or reference potential ET because it is widely grown in irrigated areas, develops crop cover early, and has an extensive root system that minimizes the effects of decreasing soil water on ET. It also provides a dense crop cover with a high stomatal conductance which results in relatively high rates of ET under arid conditions, except for a period after each cutting.

Estimation of Reference ET

Equations and procedures as modified by Wright and Jensen (1972) were used in this study to estimate maximum daily or potential ET, E_{tp}, for a well-watered reference crop of alfalfa with 20 cm or more of top growth. The modified combination equation is:

$$E^* = \frac{\Delta}{\Delta + \gamma} (Rn - G) + \frac{\gamma}{\Delta + \gamma} 15.36 (0.75 + 0.0106\ u) (e^{\circ}_z - e_z) \quad \ldots\ldots [1]$$

where E^* is the estimated daily evaporative flux, Rn is net radiation (estimated from solar radiation) and G is soil heat flux in cal/cm²·day; u is windspeed at 3.66 m (12 ft) in km/day; e°_z is the mean saturation vapor pressure in mb at maximum and minimum air temperature and e_z is the saturation vapor pressure in mb based on the 0800-hr dewpoint temperature; and Δ and γ are the slope of the saturation vapor pressure-temperature curve and the psychrometric constant in mb/° C. The coefficients in the wind term (0.75 + 0.0106 u) were developed for the 3.66-m U.S. Weather Service anemometer at Kimberly. The equivalent term for a 2-m anemometer is (0.75 + 0.0115 u). $E_{tp} = E^*/58.5$ in mm/day. Meteorological data from the U.S. Weather Service station at the Snake River Conservation Research Center, Kimberly, ID, were used to compute E_{tp} for this study because these data are normally available to users of the scheduling program. Rn was estimated from solar radiation measurements, and G from changes in daily air temperature using the procedures of Wright and Jensen (1972).

The crop coefficient as used in the USDA-ARS Irrigation Scheduling Program is a dimensionless proportionality coefficient relating daily crop ET to E_{tp}:

$$E_t = K_c E_{tp} \quad \ldots\ldots [2]$$

where E_t is the ET for a particular crop at a given growth stage and surface soil moisture condition, and K_c is the overall crop coefficient.

K_c is estimated with procedures described by Jensen, Wright, and Pratt (1971), from information on the wetness of the surface soil and availability of soil water by:

$$K_c = K_{co} K_a + K_s \quad \ldots\ldots [3]$$

where K_{co} is a mean crop coefficient derived from experimental data where soil moisture is not limiting, K_a is a coefficient whose value is relative to the available soil moisture, and K_s is a coefficient to adjust for the increased evaporation occurring when the soil surface is partially or completely wetted by irrigation or rains.

In this study, a new crop curve was developed for beans from ET data obtained with lysimeters to represent conditions when soil evaporation is minimal and availability of soil water does not limit plant growth or transpiration, i.e., $K_c = K_{co}$ with $K_a = 1$ and $K_s = 0$. In the evaluation of the accuracy of the scheduling program to estimate daily ET and soil water depletion, K_c was calculated manually by equation [3] just as the scheduling program would do using the newly derived crop curve for beans and adjusting for surface soil wetness.

Daily ET measurements for alfalfa and beans obtained with the lysimeters were used to evaluate the accuracy of the calculated E_{tp} and estimated daily ET.

RESULTS AND DISCUSSION

Alfalfa ET data from lysimeter No. 1 in 1968 and 1969 were used by Wright and Jensen (1972) to calculate the coefficients for the wind term as given in equation [1]. In the present study, daily E_{tp} calculated with these coefficients was compared with the measured ET with the same lysimeter in 1970 and 1971 for alfalfa with full cover, as shown in Fig. 1. The average measured ET for the 128 days shown was 7.23 mm/day, compared with an average calculated E_{tp} of 7.15 mm/day. The standard deviation of the difference between the measured and estimated values for this period was 0.84 mm/day, which is considered to be quite good. The nature of the difference between the measured and estimated values is further discussed by Jensen and Wright (1976).

In contrast, ET for alfalfa measured in 1973 and 1974 with lysimeter No. 2 averaged about 1 mm/day less than calculated E_{tp}. For 79 days of observation when there was full cover, measured alfalfa ET averaged 7.02 mm/day, compared with an average calculated E_{tp} of 8.13 mm/day. However, the standard deviation of the difference between the measured and calculated daily values was 0.80 mm/day, which is very similar to that for 1970-71. The average measured alfalfa ET was only 0.21 mm lower (2.9 percent), and the average calculated E_{tp} was 0.98 mm higher (13.7 percent) in 1973-74 than in 1970-71. The lower alfalfa

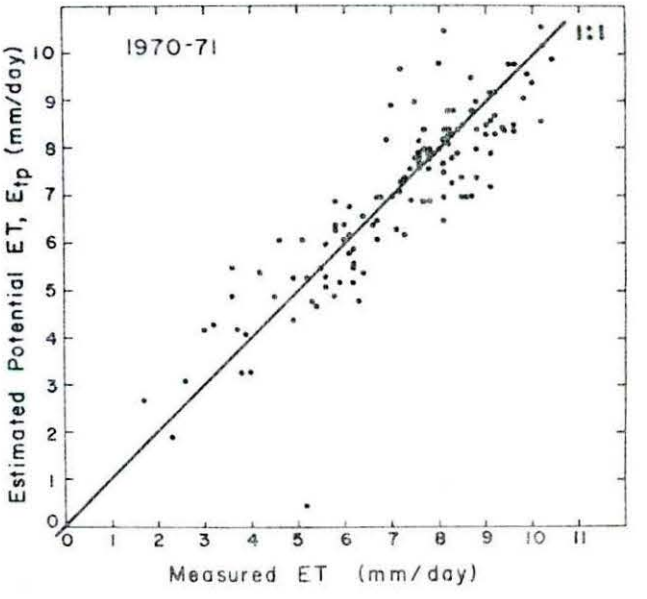

FIG. 1 Estimated potential daily ET [E_{tp}] calculated with equation 1, which is a modified Penman equation [Wright and Jensen, 1972], compared with ET measured with a weighing lysimeter for a well-watered crop of alfalfa with full cover at Kimberly, ID.

ET in 1973-74 was probably partly due to differences in the nature of the alfalfa plantings. The alfalfa on the lysimeter No. 2 field had smaller leaves, finer stems, and tended to lodge more easily during strong winds or thundershowers than did the earlier crop on lysimeter No. 1. The larger difference between the two sets of data, however, was due mainly to the much higher values of E_{tp} calculated for 1970-71. Preliminary analysis of the data indicates that this may have been partly due to yearly changes in the crops grown surrounding the Weather Service instrument plot. When short-season crops, such as grains and peas, are grown around the plot, temperatures and windspeeds are higher and humidity is lower at the measurement site during July and August than when crops such as sugarbeets, potatoes, or corn are raised nearby. The tentative correlation of conditions must be verified, but these results do demonstrate the importance of standard fetch around measurement sites where data are to be used for irrigation scheduling.

The greatest differences between measured and estimated ET tended to occur during cool and wet periods, especially if accompanied with high windspeeds. The combination equation as presently used does not adequately account for these conditions.

Development of Crop Curves

During 1973 and 1974, crops of furrow-irrigated snap beans were grown at the lysimeter No. 1 site for seed, while alfalfa was grown at the lysimeter No. 2 site. The daily E_{tp} calculated for this period with the appropriate data from the U.S. Weather Service site were used with measured Et to calculate K_c. Daily values of K_c, ET/E_{tp}, are presented in Fig. 2 for 1974, as an example. These data differ from a mean crop coefficient curve in that they include days with high evaporation from a wet soil surface. Data for 1973 and 1974 were used to develop a mean crop coefficient curve for beans, as shown in Fig. 3, where K_c is a function of time during the growing season, with the time from planting until full cover on a percentage basis (PCT), and time after full cover (DT) as elapsed days. Percentage of time is used during crop development because large difference in planting dates usually have little effect on the date full cover is reached. Effective full cover occurred about July 15 each year, or about 52 days after planting and 46 days after emergence.

The "new" curve presented in Fig. 3 essentially represents conditions when the soil surface appears dry. The considerable difference between this and the "previous" curve initially used in the irrigation scheduling program results because earlier procedures gave lower estimates of E_{tp}. The earlier ET for snap beans was calculated from soil sampling data obtained under conditions in which some deep percolation was possible and probably also included a higher component of soil evaporation from wet or partially wet surfaces. The new curve effectively reduces the estimated ET during bean leaf area development. This change should be quite beneficial, inasmuch as service groups using irrigation scheduling procedures have found that use of the previous curve along with estimates of potential ET obtained with the modified Penman equation resulted in overestimating ET. The curve was developed for a medium season, medium bush bean plant representative of a large portion of the bean crops and is applicable to other similar climatic and geographic areas.

Service groups can use some key growth points to adjust crop development to the new curve. The beans emerged about 10 days after planting at PCT = 20. The crop coefficient K_c began increasing rapidly along with leaf expansion at about the time the first trifoliates developed, or 15 days after emergence at PCT = 44 and K_c = 0.2. Bloom began about 34 days after emergence, when cover appeared to be about 50 percent (PCT = 80 and K_c = 0.55). The rows began closing about 42 days after emergence (PCT = 95 and K_c = 0.95). Full cover was reached shortly thereafter, although measured leaf area continued to increase for another 2 wks.

A polynomial regression equation was fitted to the

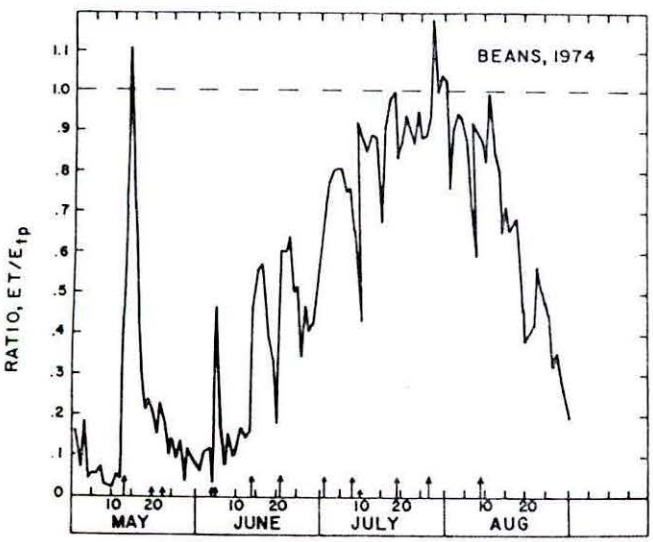

FIG. 2 Lysimeter-measured ET for furrow-irrigated snap beans raised for seed as a fraction of estimated potential ET [E_{tp}], with irrigations [large arrows] and rains [small arrows] as shown, Kimberly, ID.

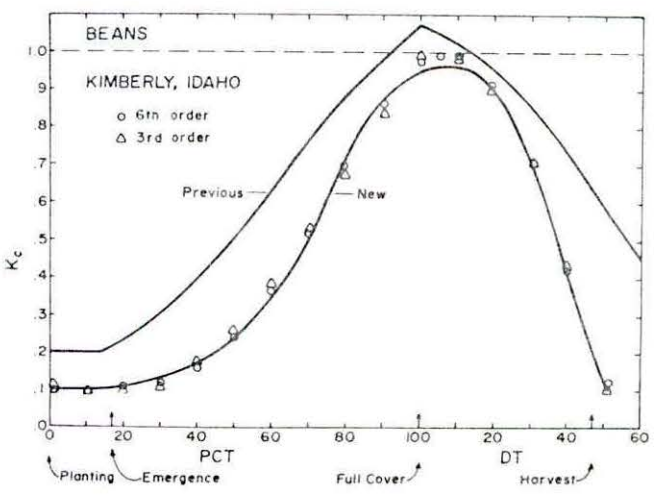

FIG. 3 A general crop coefficient [K_c] curve for beans obtained from measured ET and calculated potential ET using meteorological data. Points for polynomial regression equations are shown for a single sixth-order and two third-order [planting-full cover, full cover-harvest] equations.

new crop coefficient curve for use in the irrigation scheduling program. Third-order polynomial equations were developed for the two periods from planting to full cover and from full cover to harvest, as has been done previously. Also, a single regression equation was developed representing the entire period from planting until harvest. The coefficients for these equations are given in Table 1 for the general form of the polynomial regression equation:

$$Y = C_1 + C_2 X + C_3 X^2 + \ldots . C_n X^{(n-1)} \quad \ldots\ldots\ldots [4]$$

where Y is the crop coefficient (K_{co} of equation (3)), and X is the time base PCT or DT. In the development of these coefficients, it generally was easier to fit the curve for the period approaching full cover with a single sixth-order equation, with X = PCT or DT, depending on the period. The seven coefficients cover the entire period from planting to harvest. Points for the polynomial regression equations are shown relative to the crop curve in Fig. 3.

Evaluation of Crop Coefficients

To evaluate the ET model, we used the new crop curve and adjusted the coefficients for surface soil wetness with the procedures of the model. ET for beans was calculated with the adjusted crop coefficients, and E_{tp} as calculated from the U.S. Weather Service meteorological data.

The measured and estimated values are compared in Fig. 4. The standard deviation of the difference between the measured and estimated values was 0.95 mm/day in 1973, and 0.92 mm/day in 1974, from planting about May 20 until harvest at the end of August (103 days). The standard deviation of the difference between measured and estimated ET is essentially as good as that for the estimates of E_{tp}. Unfortunately, this is not an independent validation, since the same data used in developing the curve were used in the comparison. However, the adjustments according to surface wetness are based on independent data and the generalized crop curve was used independently for each of the years 1973 and 1974.

As an evaluation of the complete irrigation scheduling procedure, the measured and estimated depletion of soil water were compared for the 1973-74 bean crops, see Figs. 5 and 6. Depletion data shown are the accumulated daily measured and estimated ET of Fig. 4 for the periods between irrigations. It was assumed that at each irrigation soil water depletion was restored to zero. This was not entirely the case for the first two or three irrigations following emergence when rather light irrigations were applied according to usual practice. The assumption does not, however, affect the results appreciably because irrigations were scheduled well before available soil water became limiting. Water from small rains received after an irrigation was considered to be stored, accounting for the occasional extension of the lines above zero depletion. These results show that the irrigation

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TABLE 1. COEFFICIENTS FOR POLYNOMIAL EQUATIONS FOR BEAN CROP CURVE WHERE K_c IS COMPUTED AS A FUNCTION OF PERCENT OF TIME FROM PLANTING TO FULL COVER, PCT, AND OF ELAPSED DAYS THEREAFTER, DT

Third-order equation:	Before effective cover, X = PCT	
C_1 = 0.12369	C_2 = -6.0670E-03	C_3 = 2.1103E-04
C_4 = -6.2665E-07		
	After effective cover, X = DT	
C_1 = 0.9800	C_2 = 6.3783E-03	C_3 = -6.0186E-04
C_4 = 2.5268E-06		
Sixth-order equation:	Entire period, X = PCT or DT	
C_1 = 0.096444	C_2 = 1.7907E-03	C_3 = -7.0445E-05
C_4 = -6.2520E-07	C_5 = 9.4415E-08	C_6 = -1.0587E-09
C_7 = 3.1655E-12		

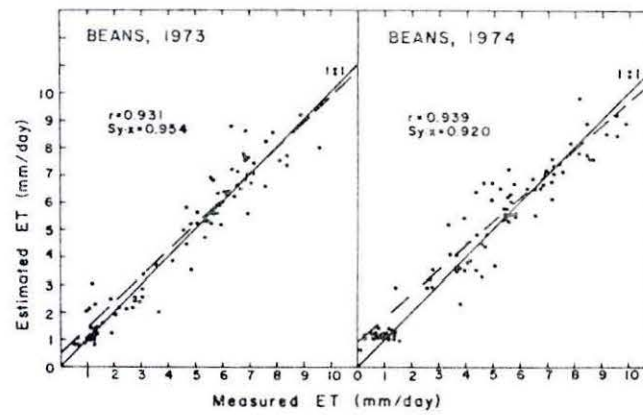

FIG. 4 Estimated ET calculated by equation [2] compared with lysimeter-measured ET for two years. Adjustment was made for wet soil surface by procedures used in the USDA-ARS Irrigation Scheduling Program.

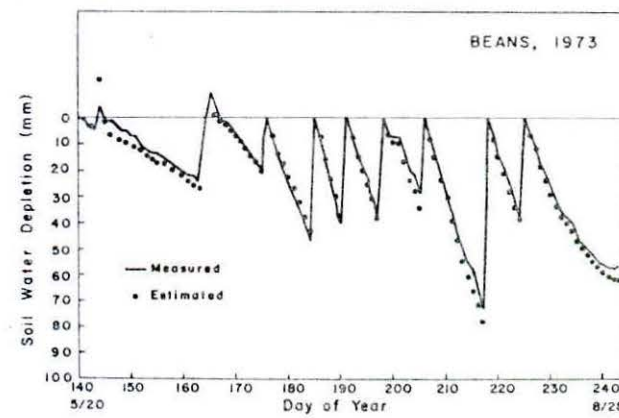

FIG. 5 Cumulative soil water depletion calculated from measured and estimated daily ET for furrow-irrigated beans, Kimberly, ID.

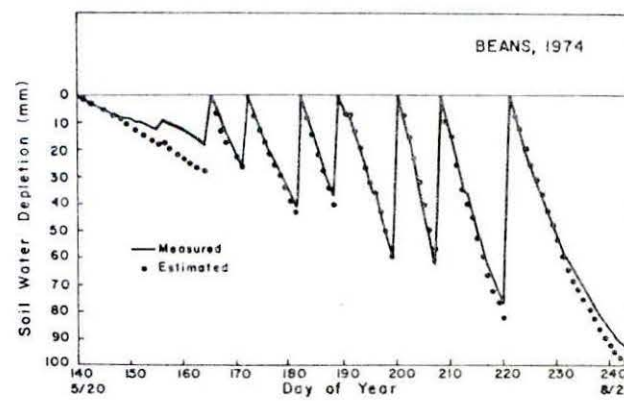

FIG. 6 Cumulative soil water depletion calculated from measured and estimated daily ET for furrow-irrigated beans, Kimberly, ID.

all basins was 7 min short of the 22 h and 15 min expected.

An inherent problem associated with the use of pneumatic systems is maintaining airtightness. Actual air usage to operate the automated system through a complete irrigation sequence is about 2.1 ml/s (0.004 ft^3/min) which does not include certain losses inherent to the operation of pneumatic values. The average amount of air supplied to the system is summarized in Table 3 for nine irrigations during 1975. Air required ranged from 0.8 to 7.3 percent of that actually supplied. Much of the losses were attributable to four-way valve leakage, a leak in an air-control line leading to jack-gate 3, and air by-pass within the air cylinders. Most of the first two causes were eliminated before the 29 July irrigation, with only air by-pass within the cylinders still occurring after that date. The air demands of 28 ml/s (0.06 ft^3/min) are not too serious and are easily met by the air compressor used. New, commercially available, air cylinders (one of which has been used on the check gate since July 1975 without measurable air by-pass) have replaced the locally constructed cylinders.

COST

The cost of materials and trenching required to convert the jack-gates from manual to automatic was about $3,300 or $124/ha ($50/acre, 1976 prices). No information is available, however, on total installation costs. It should be noted that the equipment used could feasibly satisfy the requirements for a much larger acreage, depending on the particular irrigation layout.

SUMMARY AND CONCLUSIONS

A 26.3-ha (65-acre) field, divided into eight level basins that are independently irrigated from a centrally-located, concrete-lined canal using single outlet jack-gates, has been automated with pneumatic controls and air cylinders. The system has been successfully used during 17 irrigations (May 1975 through October 1976). The last 15 irrigations were completed by the farmer and/or his irrigator without assistance from the developers.

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scheduling procedure with the new K_C curve adequately estimates soil water depletion between irrigations, especially during the main part of the season when there is active plant growth and full plant cover. Some problems remain in estimating evaporation from bare soil early and late in the season, as shown by the deviation between the estimated and measured values during those times.

CONCLUSIONS

Results of this study confirmed the earlier evaluation of the USDA-ARS Irrigation Scheduling Program and showed that the expected errors in estimating potential ET are well within acceptable limits. The improved crop coefficient curve for snap beans greatly improved the evapotranspiration estimates for snap beans; the expected error in estimating daily ET is about the same as that in estimating the potential or reference daily ET. As more information and experience are obtained on the water requirements of irrigated crops, improvements and greater capability can be incorporated into these procedures, but for the present they are generally more than sufficient to meet the capability of irrigation systems to apply specified quantities of water. The combination equation, which is a convenient way of estimating evapotranspiration for crops with full cover, tends to overestimate potential ET when the season is cool and wet, and refinements are still needed in estimating the soil evaporation component when there is only partial cover. Work is continuing to provide improvements in these areas and to develop crop coefficients for other crops.

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