TECHNICAL COMPLETION REPORT

REMOTE SENSING FOR IRRIGATED CROP WATER USE PHASE 1

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OBJECTIVES AND GENERAL PROCEDURE

This report constitutes the final report on Remote Sensing for Irrigated Crop Water Use-Phase 1 under the revised Joint Research Interchange project involving Ames Research Center and the University of Idaho.

The goal of this research is to identify specific evapotranspiration models and model input parameters which have potential for estimation using remote sensing data. Also, a goal is to determine if regional ET estimates can be made directly from a remote sensing based measure of vegetation, such as crop type or group, biomass, or leaf area. The effort includes input and data from NASA/ARC, Idaho Department of Water Resources, and the University of Idaho.

In recent years, several models have been proposed as methods of evaluating regional ET utilizing remotely-sensed crop canopy temperatures. Results have indicated that such ET estimates are feasible if functional relationships can be found providing reasonable estimates of ET based on indirect measurements of factors which control ET. The test of remote sensing capability along these lines is now needed to provide guidance for further research efforts.

Methodology to estimate crop ET from ground-sensed meteorological data has progressed in recent years. Several methods are now available with the degree of accuracy depending primarily on the degree of data availability.

Methods for estimating crop water use are needed because of the difficulty in obtaining accurate field measurements. To obtain accurate estimates of ET for a specific crop, the major crop and environmental conditions need to be considered. One approach which has been successful provides estimates of crop water use on a field basis utilizing a reference crop ET and an ET crop coefficient. Meteorological conditions establish the evaporative demand while existing crop canopy and soil moisture conditions determine the extent to which that demand is met. The reference crop ET (ETR) characterizes general evaporative conditions, while the crop coefficient (KC) provides a means of relating actual crop ET (ETC) to that reference.

There has been extensive research on reference ET methods and crop coefficients because of their application in irrigation scheduling and water resources allocation, management and planning. The presently available methods permit estimates of crop ET which are within the accuracy of most field irrigation systems to deliver water (Jensen et al., 1971; Jensen, 1975; Jensen and Wright, 1978; Wright and Jensen, 1978). Various experimental crop coefficients and procedures for determining reference ET data have been reported (Jensen, 1974; Doorenbos and Pruitt, 1977; Burman et al., 1980; Wright, 1979, 1981, and 1982).

The data used for this task were collected in long-term field experiments at Kimberly, Idaho, to determine the relationship between crop water requirements and crop, soil, and climatic conditions. The crop factors studied included the crop type, stage of growth, and amount of plant material or dry matter yield. Soil factors included surface soil wetness, the soil water holding capacity, and rooting depth. Meteorological conditions included the parameters usually measured at established, major weather stations such as temperature, humidity, windspeed, and solar radiation. Results were previously used in development of the procedures for estimating a daily reference crop ET using meteorological data, and a unified set of ET crop coefficients (Wright, 1981, 1982).

The effort by the University of Idaho focused on three specific tasks:

EVAPOTRANSPIRATION (ET) MODEL SENSITIVITY ANALYSIS

An evaluation of the sensitivity of existing evapotranspiration models to climatic input parameters which had potential for estimation by remote sensing was conducted. Four site specific ET models were used and sensitivity of crop coefficients and estimated reference ET to temperature, solar radiation, dewpoint and wind speed were evaluated. A complimentary approach, which has been used to estimate regional evapotranspiration based on the interaction between evaporating surfaces and the ambient air was also evaluated. This procedure is not well documented and accepted by the scientific community and because of the low anticipated potential for success, a full evaluation was not performed.

No effort was made by the University of Idaho to develop information on sensor resolution, data availability or the feasibility of calculation of input variables from different types of remote sensing data.

CROP TYPE VERSUS CROP GROUP ET ESTIMATES

Recognizing that Landsat data can be used to identify major crops and/or crop groups, the similarity of ET among groups was evaluated. Crop groupings and mean individual pixel accuracy for a group using multidate Landsat MSS data were furnished by the Idaho Department of Water Resources and crop coefficients for each group determined from individual crop coefficients. Each group crop coefficient was determined assuming equal percentages of each crop within a group and potential monthly and seasonal crop coefficient and ET errors were determined using a 14 year weather data base for Kimberly, Idaho. Maximum errors were assumed to occur when the one crop within the group with the highest or lowest ET was the only crop actually present in the group.

RELATIONSHIP BETWEEN CROP BIOMASS/LEAF AREA AND CONSUMPTIVE WATER USE

Using data collected on lysimeters and field experiments at Kimberly, Idaho, the relationships between leaf area index and dry matter or biomass were evaluated for various crops. Attempts were made to define the linear responses of leaf area index and biomass to crop ET and develop empirical relationships including time of planting and maturity dates.

SENSITIVITY OF ET ESTIMATION METHODS

Reference ET is the evapotranspiration from a specifically defined well watered crop, usually grass or alfalfa. Reference ET serves as a standard for calculation of actual ET from other crops. Actual crop ET is determined as the product of reference ET times an empirically determined crop coefficient. Reference ET is intended to incorporate all climate and soil effects, and crop coefficients account for physiological differences between crops. Numerous methods have evolved for estimation of reference ET. Methods differ in definition of reference crop, their complexity, and in their data requirements. The appropriate method for any given application or location depends upon data availability and the desired accuracy of results.

Reference ET estimation methods are usually limited by availability of necessary weather data. Weather stations often do not collect all the data required and represent climatic conditions only at discrete, sparsely located points within an area. Remote sensing may provide additional information which will supplement that collected at weather stations, or assist in extrapolation of station data. This provides an opportunity for improved estimation of regional evapotranspiration. The applicability of remote sensing to ET estimation is dependent upon the accuracy attainable in sensing individual parameters and the sensitivity of estimation methods to errors in input parameters. This section describes the sensitivity of four commonly used estimation methods to errors in climatic parameters.

PURPOSE AND OBJECTIVES

Remote sensing is best applied to ET estimation methods in which the primary dependence is on parameters which can be sensed with a high degree of confidence. Methods which demonstrate a strong dependence on parameters which cannot be sensed, or sensed only with a relatively large error are less compatible with remotely sensed data. The purpose of this task was to describe the sensitivity of ET estimation methods to errors in climatic input data. The objectives were:

1. To evaluate sensitivity of several methods to errors in individual climatic parameters,
2. to compare sensitivity of the various methods, and
3. to describe how sensitivity varies with changing base conditions.

PROCEDURE

Four ET estimation methods were selected for sensitivity evaluation. The methods were FAO Blaney Criddle, FAO Radiation, Jensen-Haise, and Wright-1982. The FAO (Food and Agriculture Organization) procedures were originally described by Doorenbos and Pruitt (1977). Descriptions of all procedures included in Allen and Brockway (1983). Calculations for all methods were performed by the FAO 24 computer program described by Allen and Brockway (1983).

Monthly means of unpublished daily climatic data from the National Oceanic and Atmospheric Administration (NOAA), Twin Falls Weather Service Office (WSO) for the 14 year period of 1965 through 1978 were used as base data for the sensitivity analysis. Data included in the analysis were maximum and minimum temperatures, dew point, global solar radiation, and wind speed. Sensitivity was tested by individually adjusting values of one parameter while holding other parameters at the monthly mean values. Mean monthly data were used rather than daily values to avoid daily extremes where adjusted values may exceed some physical limits such as solar radiation exceeding clear day solar. Parameter adjustments were usually restricted to the physical limits of the parameter. Average monthly ET was summed to determine cumulative effects over the growing season. Errors are presented in percent of base condition ET to avoid confusion over comparison of different reference crops.

RESULTS

Results of sensitivity analysis were determined for each month and cumulative values averaged for the growing season. Monthly means for each parameter are given in Table 1. Changes in base conditions are responsible for differences in sensitivity between months.

Table I. Mean monthly climatic data, Twin Falls WSO, 1965-1978.

Month	Mean Daily Temperature (°F)	Dew Point (8 A.M.) (°F)	Solar Radiation (langleys/day)	Wind Speed (mpd)
April	45	29	475	229
May	54	37	583	195
June	62	44	627	167
July	69	50	644	131
August	67	47	551	131
Sept	57	38	445	146
Oct	47	30	314	154

Evapotranspiration calculated by the four methods differs due to different procedures and use of different reference crops. Allen and Brockway (1983) calibrated monthly correction coefficients which compensate for both differences. Estimates generated by the Wright-1982 method are probably most accurate, partially due to the local calibration of the equation. Estimates for each month and equation are given in table 2.

Table 2. Mean monthly reference evapotranspiration, Twin Falls WSO, 1965-1978.

Month	FAO Blaney-Criddle[1]	FAO Radiation[1]	Jensen-Haise[2]	Wright 1982[3]
April	3.50	4.09	2.94	4.20
May	5.46	5.80	4.84	6.21
June	6.99	6.78	6.28	7.54
July	7.93	7.36	7.38	7.99
August	6.81	6.19	6.05	6.84
September	4.76	4.48	4.01	5.12
October	2.67	2.64	2.15	3.19

[1] grass reference

[2] unspecified reference crop

[3] alfalfa reference

Temperature Sensitivity

The sensitivity of all four ET estimation methods to changes in monthly mean maximum and minimum daily temperatures was determined within a range of $\pm$16°F. Temperature data is used directly in the estimation equations, and may also affect other parameters. Temperature affects net radiation, soil heat flux, and vapor pressure deficit calculations in the Wright-1982 method. It also affects relative humidity calculations with the FAO-Blaney Criddle and FAO-Radiation methods.

The average seasonal sensitivity on a relative basis (% ET change) is shown in figure 1. The FAO-Blaney Criddle methods exhibits the greatest sensitivity since it is primarily a temperature dependent method. The FAO-Radiation method is least sensitive. Most methods show a nearly linear response to temperature change; however, the response of the FAO-Radiation method is inflected at a temperature change of about -4°F. The inflection results from minimum daily temperature affects on relative humidity. This method does not permit dew point to exceed minimum daily temperature.

Base climatic conditions have a significant effect upon sensitivity. That is, sensitivity at one set of temperatures, dew point, solar, and wind data is different than for a second set. Sensitivity plots of each method for each month are presented in the appendix. Monthly variations, caused by changing base conditions, are summarized by figures 2 and 3 which show relative and absolute sensitivities to an +8°F change in temperature. The absolute change is greatest during midsummer, however, the relative sensitivity is least during this period due to the elevated ET rate. The absolute change plotted in Figure 3 incorporates effects of different reference crops used with the different methods, complicating comparisons between methods. Figures 2 and 3 show that an error in sensing or measuring average monthly July temperature of +8°F would result in a 17% error in estimated reference ET, or an absolute

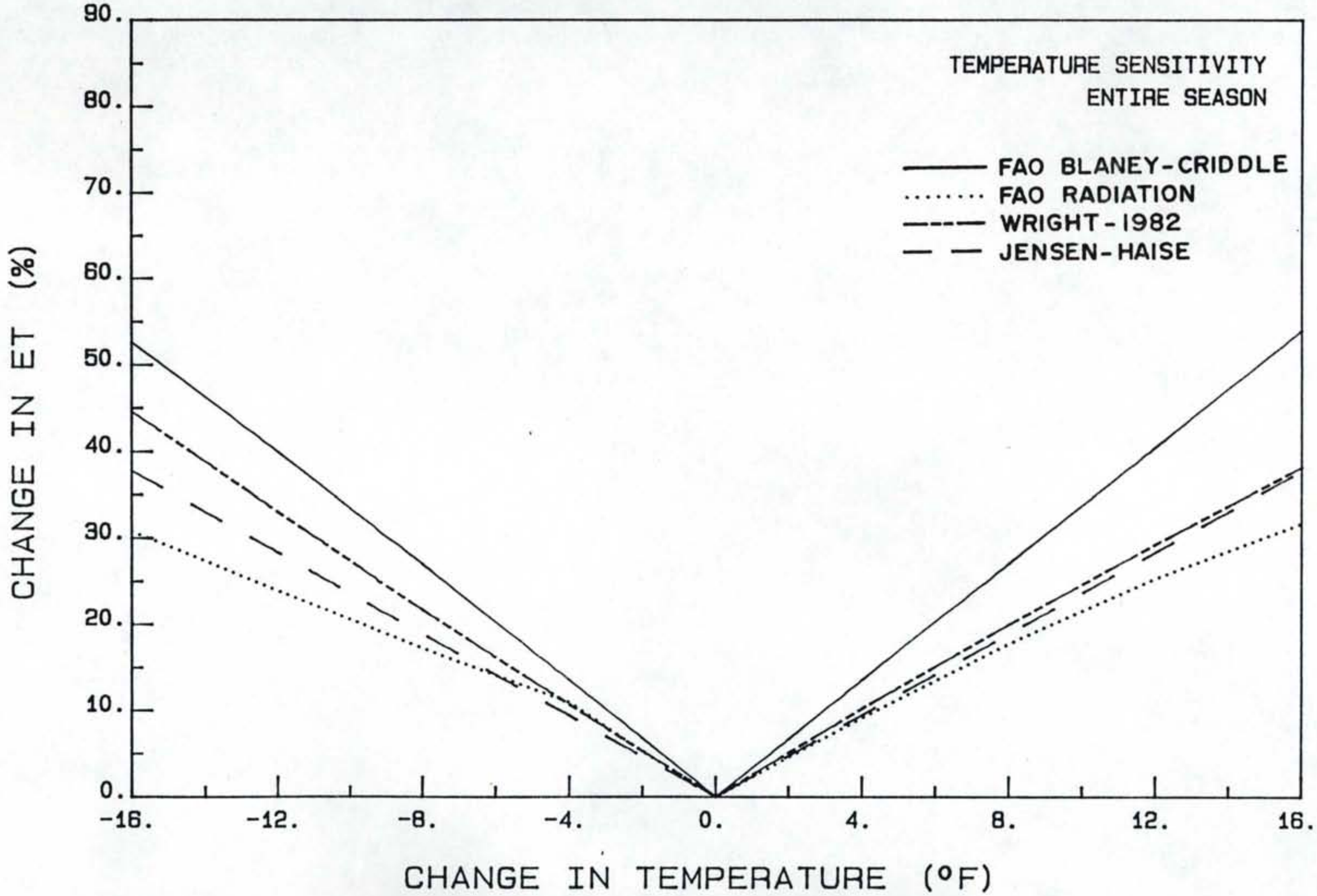

Figure 1. ET sensitivity to temperature for entire season, Kimberly, Idaho.

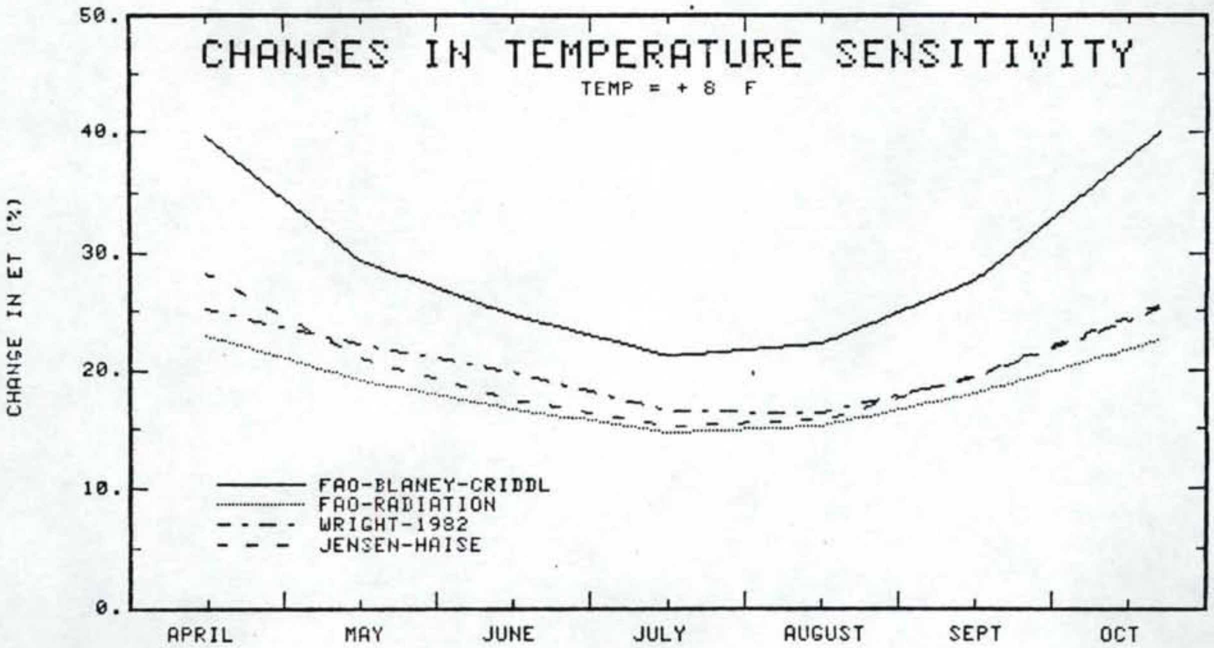

Figure 2. Relative sensitivity of ET to a +8°F change in temperature.

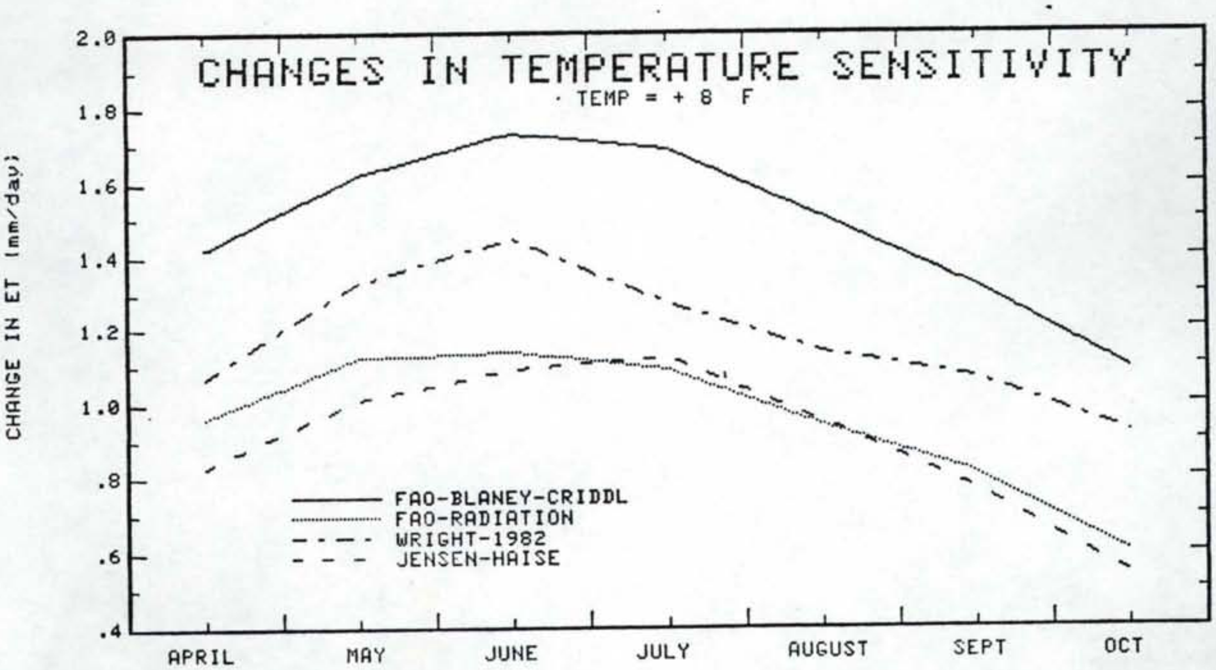

Figure 3. Absolute sensitivity of ET to a +8°F change in temperature.

error of +1.5 mm/day using the Wright 1982 procedure. Differences in ET rates by method, including reference crop effects, are given in Table 2.

Dew Point Sensitivity

Dew point sensitivity was evaluated for the FAO-Blaney Criddle, FAO-Radiation, and Wright-1982 methods. The Jensen-Haise method does not include dew point or vapor pressure parameters and consequently was not included in the analysis.

The average seasonal response of calculated ET to dew point change is plotted in Figure 4. All 3 methods exhibit non-linear relationships. The response to lower dew point (negative changes) is similar for all methods, resulting in probably negligible differences in sensitivity within that range. The Wright-1982 and FAO-Blaney Criddle methods display an increased sensitivity to increases in dew point resulting from the non-linearity of the temperature-saturation vapor pressure relationship. Dew point temperature increases greater than minimum daily temperature are unrealistic and sensitivity beyond minimum daily temperature is of no concern. The FAO-Radiation method shows a discontinuity in slope at a change of +4°F. This is the point where dew point temperature usually exceeds minimum daily temperature. Dew point remains about 5°F below minimum daily temperature (at Kimberly) throughout the year as is apparent from the monthly dew point sensitivity graphs shown in the appendix.

Dew point sensitivity (relative % ET) is not greatly affected by base conditions with any of the selected methods (figure 5). The

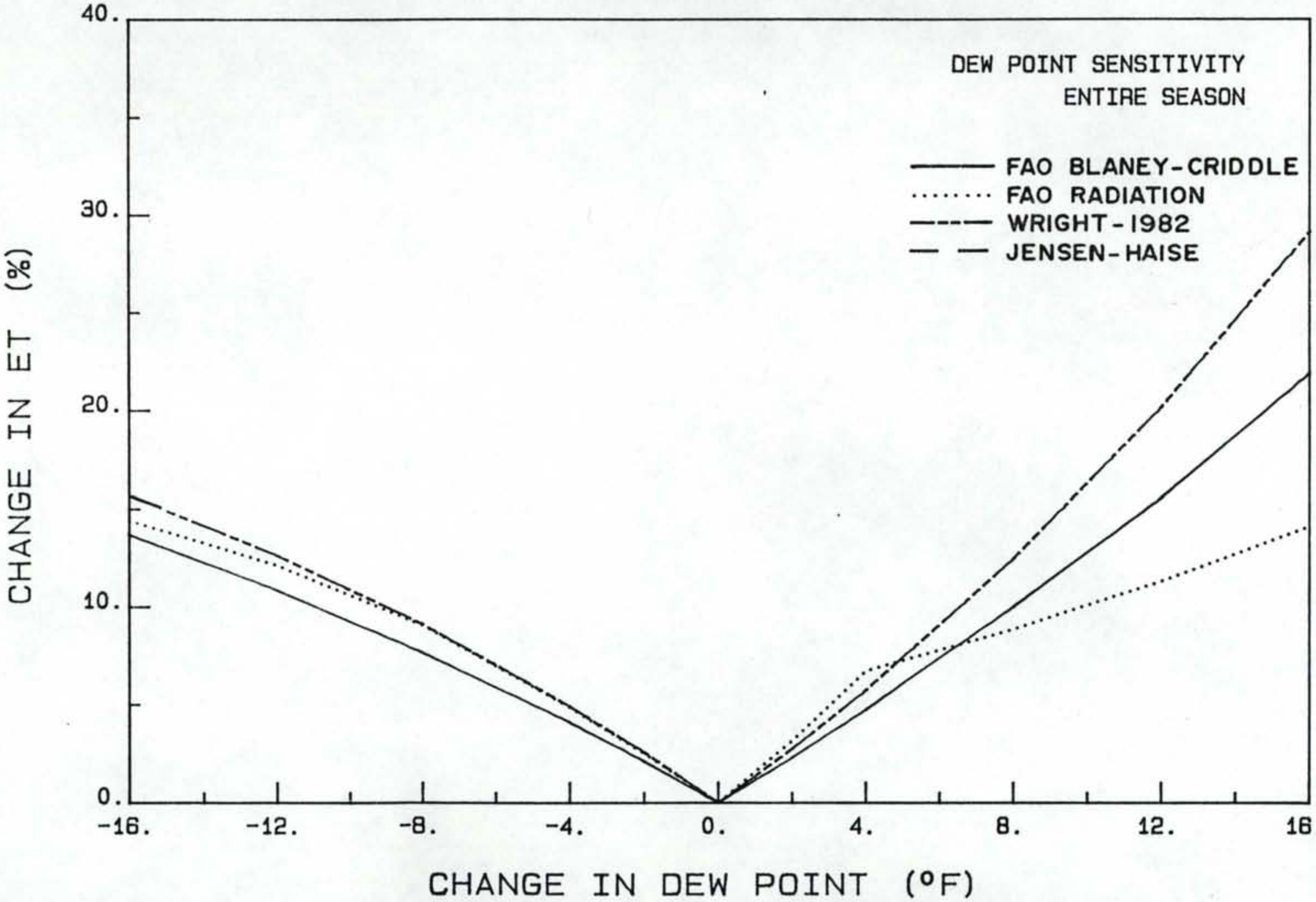

Figure 4. ET sensitivity to dew point for entire season, Kimberly, Idaho.

relative percentage of ET change due to a -12°F dew point change is +12 to 15% with the least change occurring during late summer. The absolute change (figure 6), however, shows an increased significance during July and August, corresponding to a higher ET rate during this period. Differences between methods in Figure 6 are partially due to the use of different reference crops. Sensitivity in each month for a range of dew point temperatures is shown by figures in the appendix.

Solar Radiation Sensitivity

The sensitivity of all four ET estimation methods was evaluated within a range of ±90 langleys/day of the monthly mean solar radiation values. The seasonal average of the calculated ET response is shown in Figure 7. The seasonal average response of most methods is nearly linear. The Wright-1982 method, however, shows an irregularity resulting from decreases in solar radiation. The irregularity is caused by an incremental change in a coefficient used in calculation of emitted thermal radiation. The coefficient changes when the ratio of solar radiation to clear day radiation becomes less than 0.7. The irregularity is dampened in the seasonal average and is more apparent in the monthly graphs in the appendix.

The FAO-Radiation and Jensen-Haise methods are primarily radiation based, and consequently show the greatest sensitivity to changes in radiation. The Wright-1982 method exhibits the least sensitivity. The ratios of ET change to changes in solar radiation are given in table 3. Ratios were prepared by approximating all relationships as linear within the range of interest.

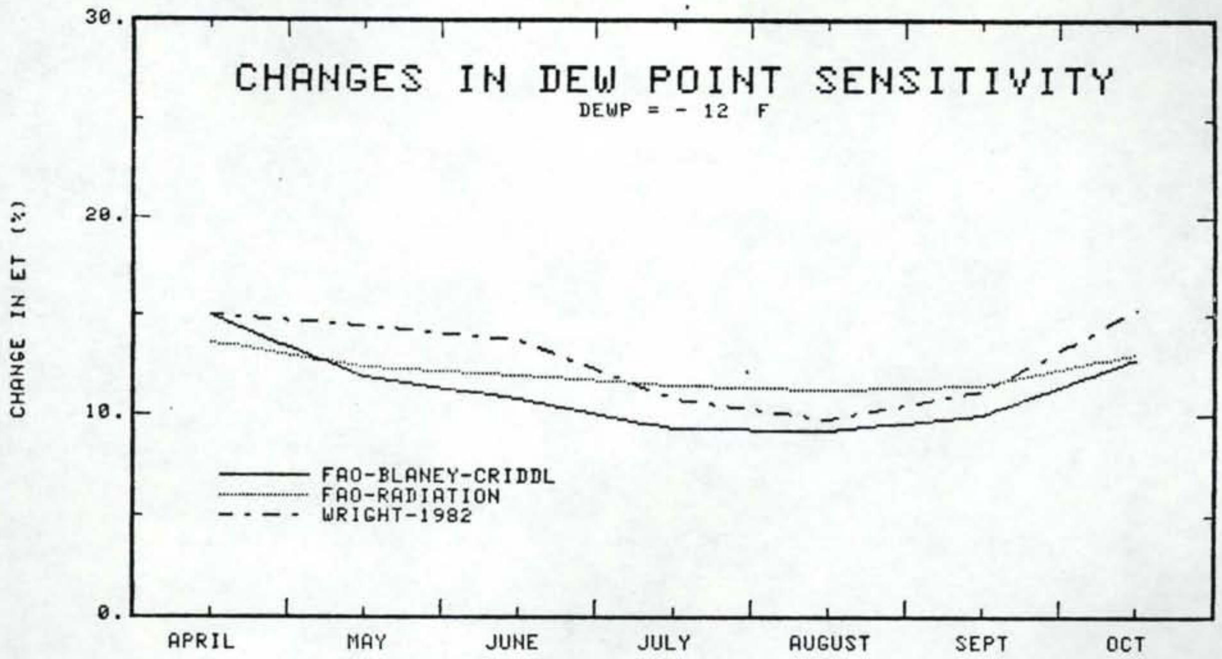

Figure 5. Relative sensitivity of ET to a -12°F change in dew point.

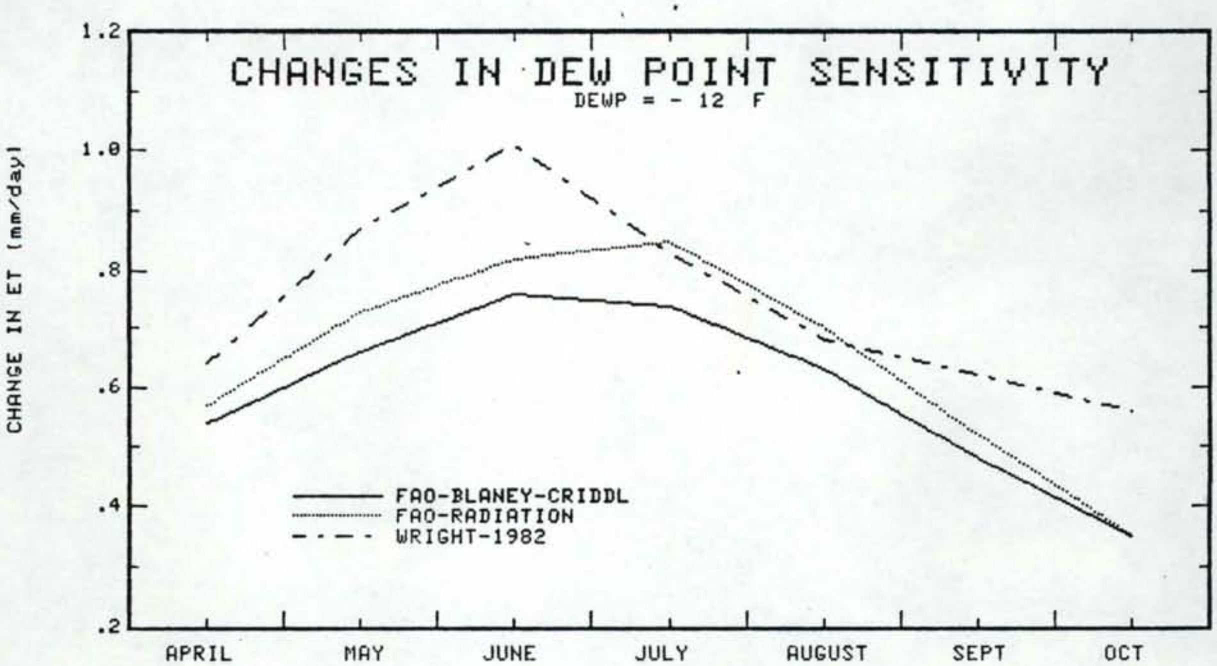

Figure 6. Absolute sensitivity of ET to a -12°F change in dew point.

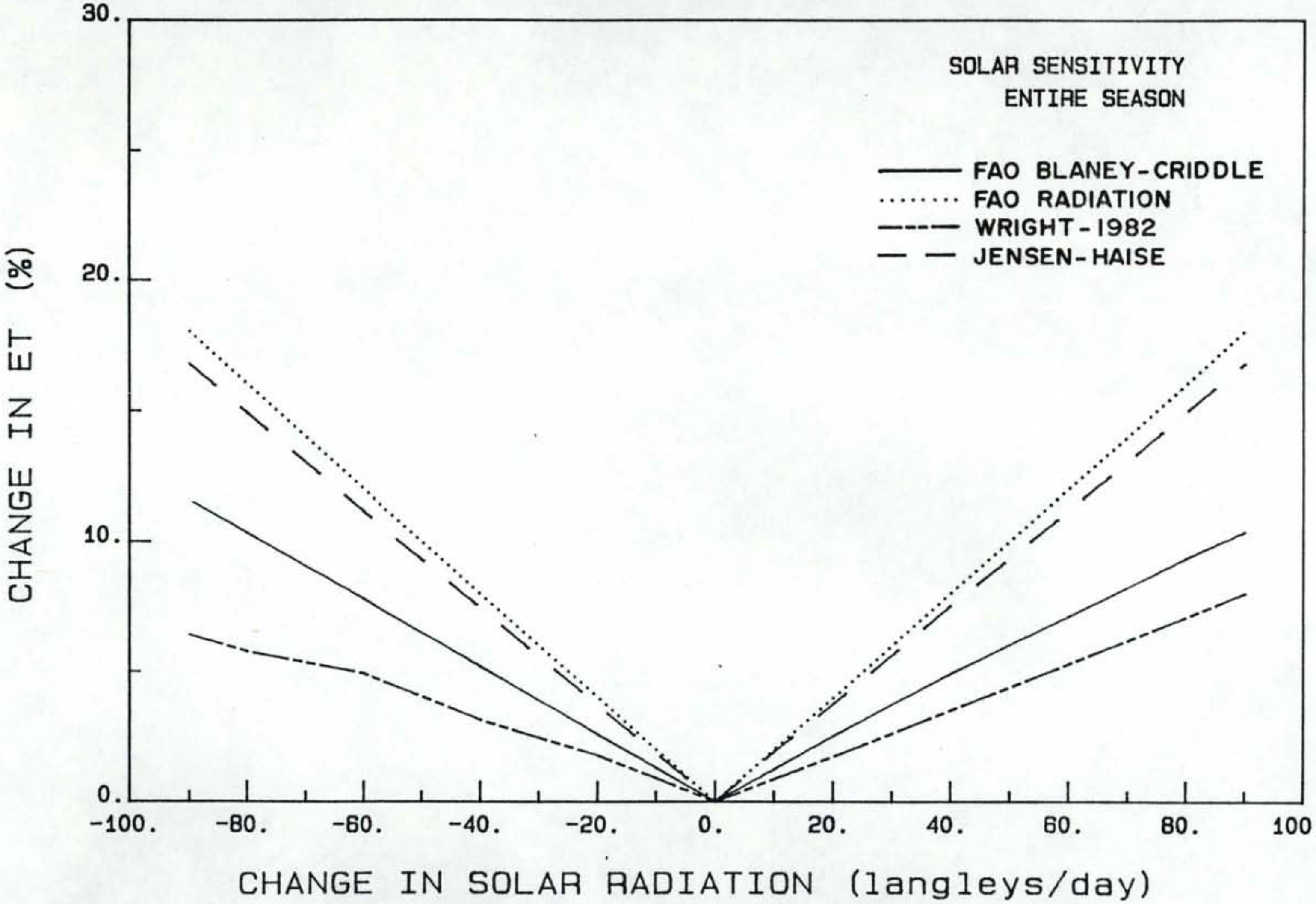

Figure 7. ET sensitivity to solar radiation for entire season, Kimberly, Idaho.

Table 3. Solar radiation sensitivity ratios.

Method	ΔET(%)/ ΔSolar(langleys/day)
FAO - Radiation	20.0×10^{-2}
Jensen-Haise	18.7×10^{-2}
FAO-Blaney Criddle	11.6×10^{-2}
Wright - 1982	8.9×10^{-2}

Changes in solar radiation sensitivity throughout the year are shown in figure 8 on a relative scale and figure 9 on an absolute scale. Absolute sensitivity is consistently greatest during peak ET months of July and August. Relative to monthly ET, however, sensitivity is generally least during this period. In the fall, when radiation is lowest (during the growing season) an absolute change of 80 langleys/day represents a larger percentage of incident radiation and of the total energy available, resulting in a magnification of the relative effects. The Wright-1982 method emphasizes the aerodynamic term more during fall, resulting in less of a relative increase than is apparent with other methods.

Wind Speed Sensitivity

The Jensen-Haise method does not incorporate wind speed and was, therefore, not included in the analysis. Average seasonal sensitivity of the remaining three methods is plotted in figure 10. The Wright-1982 method is most sensitive and the sensitivity is linear. On a seasonal average, the Wright-1982 method has a 2.1% change in calculated ET for each 10 mph change in wind speed, assuming all other conditions remain constant. The FAO-Blaney Criddle and FAO-Radiation methods are non-linear and slightly more sensitive to negative changes in wind speed.

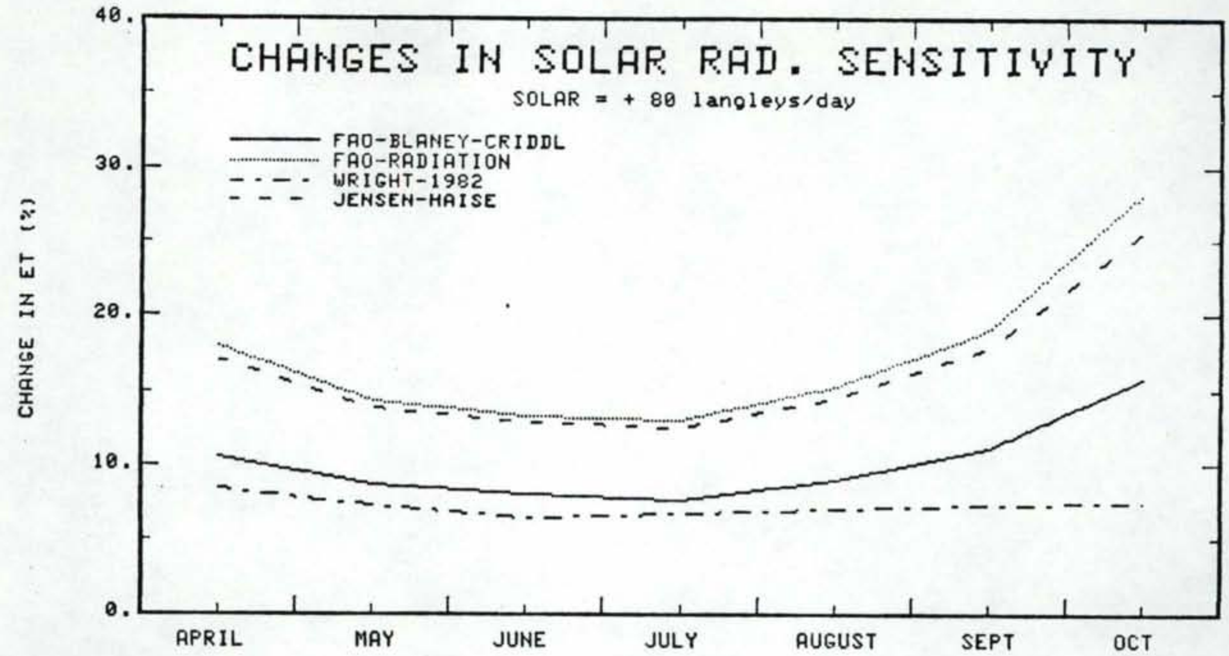

Figure 8. Relative sensitivity of ET to a +80 langleys/day change in solar radiation.

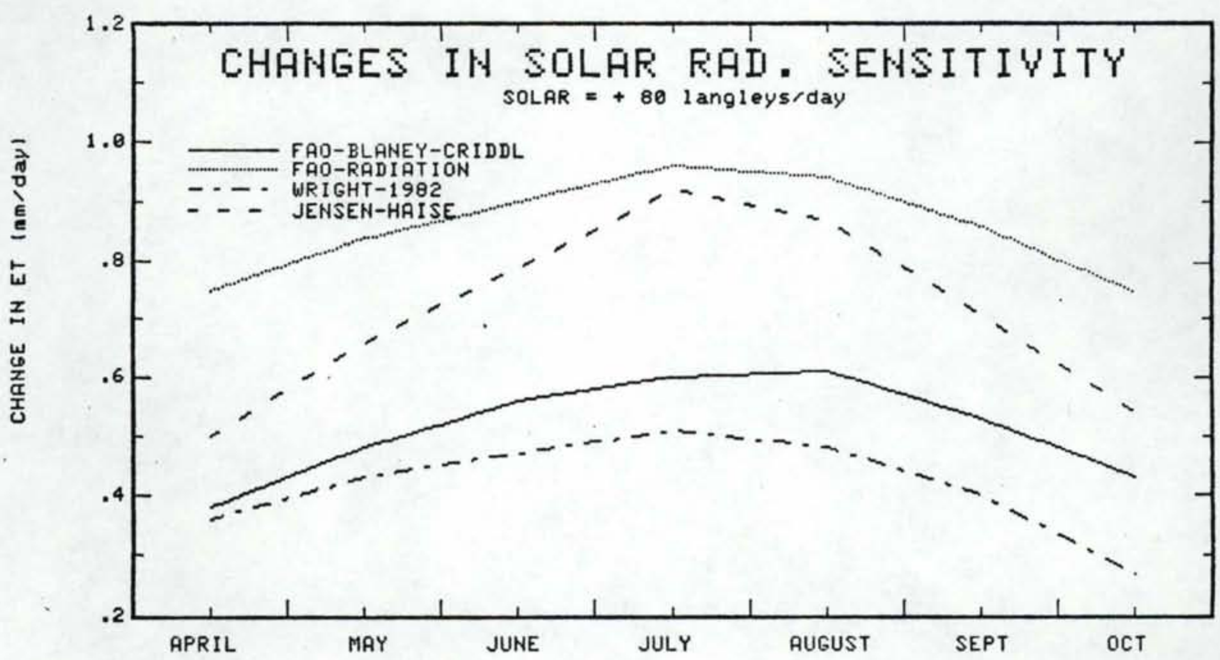

Figure 9. Absolute sensitivity of ET to a +80 langleys/day change in solar radiation.

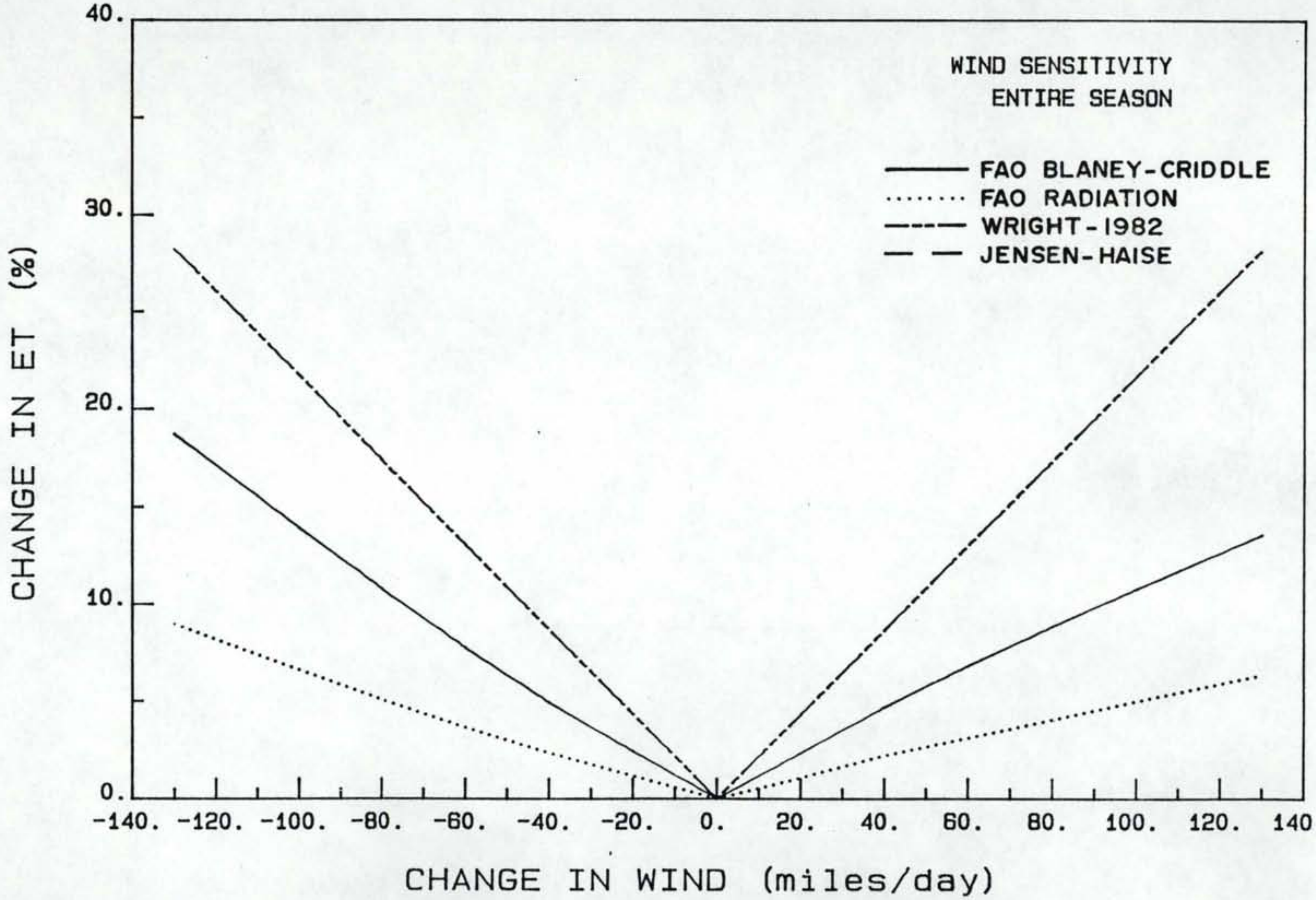

Figure 10. ET sensitivity to wind for entire season, Kimberly, Idaho.

Changes in relative and absolute sensitivities throughout the season are shown in figures 11 and 12 for a 100 mi/day wind increase. The Wright-1982 method shows the greatest change, increasing through the year on a relative basis. The increase is due to lower average wind speeds in the summer and fall and an increasing dependence on the aerodynamic term later in the year. Wind is a secondary parameter in the FAO methods and is used to calculate a multiplier. Wind significance in the calculations is only slightly affected by changes in the other parameters as evidenced by the relatively flat appearance of the graphs.

Sensitivity Summary

Different ET estimation methods are sensitive to changes in different climatic parameters. The average seasonal sensitivity of each of the methods to each parameter is listed in table 4 for a specific magnitude of change.

Table 4. Seasonal Sensitivity Summary.

Parameter	Change Increment	Seasonal ET Change (%) FAO-BC	FAO-Rad	Wright	J-H
Temperature	+8°F	27.0	17.8	20.0	18.9
Dew Point	-12°F	10.8	12.1	12.6	0.0
Solar Radiation	+80 l/d	9.3	16.0	7.1	15.9
Wind Speed	+100 mi/d	10.8	5.0	21.7	0.0

Selection of a method for use with remote sensing must consider the accuracy of the estimating method, and the potential for using long term averaged data instead of measured values of secondary parameters. Allen and Brockway (1983) found the FAO Blaney Criddle to perform reasonably

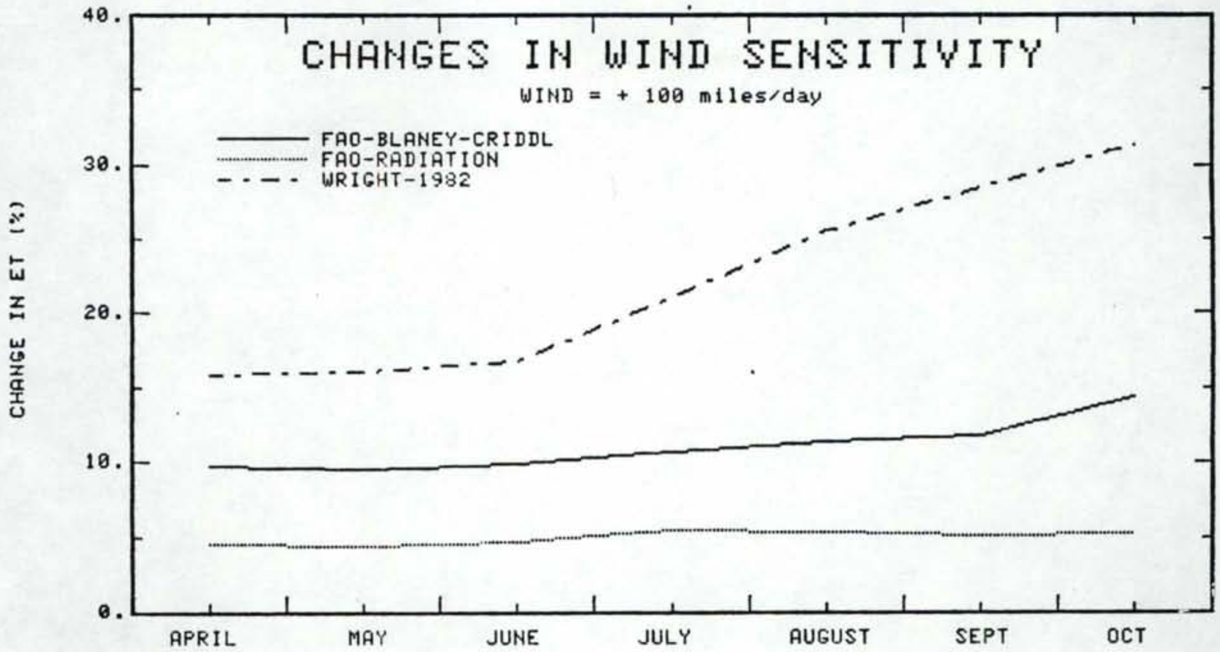

Figure 11. Relative sensitivity of ET to a +100 miles/day change in wind.

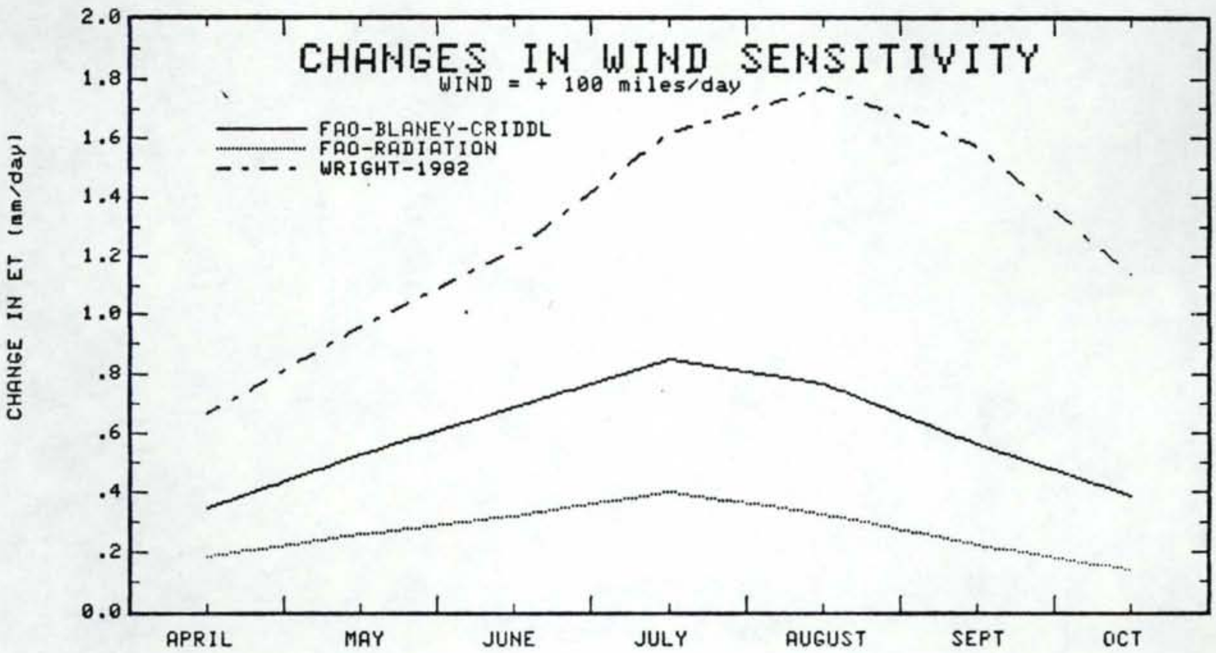

Figure 12. Absolute sensitivity of ET to a +100 miles/day change in wind.

well using long term average solar radiation, dew point, and wind speed. Availability of crop coefficients compatible with the selected method must also be considered.

Sensitivity changes with the base conditions under which it is evaluated. Sensitivity for one set of temperature, dew point, radiation, and wind will differ from sensitivity at a second set. The conditions of the application must, therefore, be known in order to establish the exact sensitivity of the methods. Sensitivity of estimated monthly ET at Kimberly, Idaho to changes in temperature, dew point, solar radiation, and wind are shown in figures A-1 through A-28 in Appendix A.

CROP COEFFICIENT GROUPING

Crop coefficients are the ratio of actual ET for the particular crop to reference ET. Actual ET for a crop is estimated as the product of the crop coefficient times the reference ET. Crop coefficients vary with time and crop development. The distribution of coefficients over the season is called the crop curve. Crop curves, determined by Wright (1982), are shown in figure 13. Crop coefficients are empirically determined for a specific reference crop, and should only be used with the appropriate reference ET.

Crop coefficients may represent basal or mean conditions. Basal crop coefficients are determined for a dry soil surface which contributes little to total evapotranspiration. Evaporation from the soil surface must be calculated separately when using basal coefficients. Basal coefficients are best suited for estimating daily ET from a specific field where evaporation is highly variable, depending on moisture conditions. Mean crop coefficients temporally distribute the average effects of soil evaporation. Mean coefficients are applicable to estimating average ET for long periods or large areas, and are used in this project.

Remote sensing may be used to determine relative areas of crops or crop groups within a defined area. Crops may be classified into groups based upon similarities in spectral response.

Two forms of error may occur in estimating crop coefficients by remote sensing, recognition error and grouping error. Recognition error

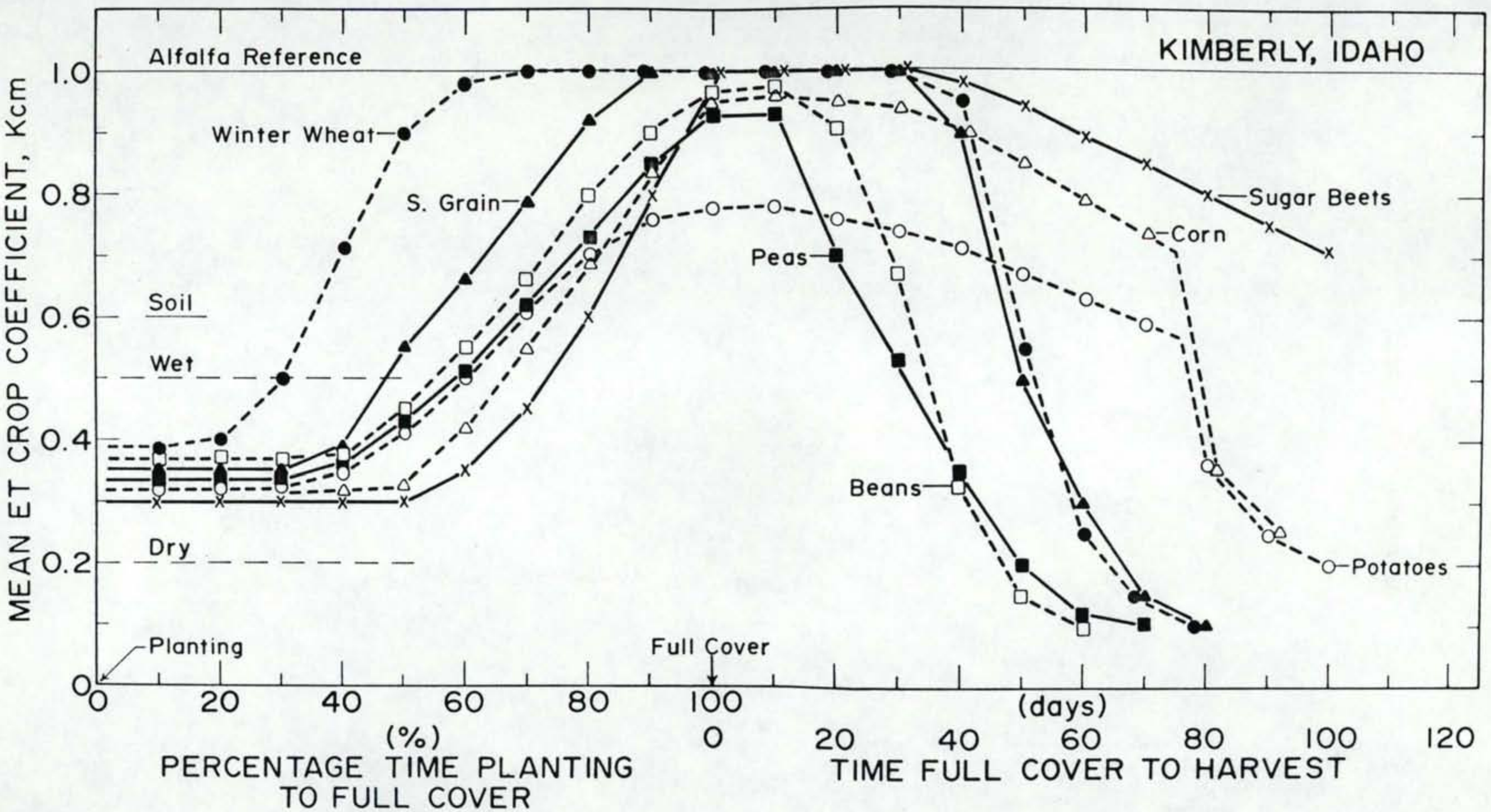

Figure 13. Mean crop coefficient curves.

is error resulting from difficulties in discrimination between the spectral response of crop groups. Grouping error is caused by representing multiple crops with a single crop curve. As broader crop groups are used, recognition error tends to decrease and grouping error increases.

This project was designed to estimate maximum potential crop grouping error. The crops evaluated are limited to those grown in southern Idaho, having comparable and published crop curve information.

PROCEDURE

Crop grouping errors were estimated using mean crop coefficients (alfalfa reference) for crops of southern Idaho. Daily coefficients were determined for specific crops using average crop development data for Kimberly, Idaho (Allen and Brockway; 1983) in conjunction with normalized crop curves developed by Wright (1981). That is, average planting cover and harvest dates were used to interpolate daily crop coefficients from published tables.

Maximum grouping errors were estimated for each selected crop group. It was necessary to express maximum potential error since actual errors are dependent on the relative percentage of each crop present within the study area. For example, if a crop group includes peas, beans, and potatoes, and the study area contains an equal percentage of each crop, then no error is introduced by representing the group by the average crop curve. If, however, the study area consists entirely of peas, substantial error results from using the average crop group curve.

An unlimited number of areal percentages are possible depending upon the study area. It was therefore determined to present only the error limits. That is, the maximum differences in crop coefficients that can occur in each crop group. Maximum error at any time is the difference between the average curve (crop group) and the maximum or minimum extremes. The results are plotted on a seasonal basis since the relationships are time dependent.

Crop grouping error is expressed both in terms of crop coefficients and in the effects on calculation of actual ET. Grouping error has a more pronounced effect during mid-season when reference ET is near a maximum. Unpublished weather data (1965-1976) from the Twin Falls WSO were used in the Wright-1982 combination equation to estimate average weekly alfalfa reference ET. The reference was multiplied by weekly average crop coefficients to determine effects of grouping error on calculated actual ET.

Crop groups were selected based on spectral similarities and the availability of crop coefficients of a common reference. The selected groups are described in Table 5.

Table 5. Crop Group Definition.

Group	Crops
1 Green Crops	alfalfa hay, seed alfalfa, grass pasture, beans, peas, sugar beets, field corn, sweet corn, potatoes
2 Row Crops I	beans, peas, sugar beets, field corn, sweet corn,potatoes
3 Row Crops II	beans, peas, field corn, sweet corn, potatoes
4 Beans & Peas	beans, peas
5 Corn	field corn, sweet corn
6 Small Grains	winter wheat, spring wheat and barley
7 Alfalfa & Grass	alfalfa hay, seed alfalfa, grass pasture
8 Alfalfa	alfalfa hay, seed alfalfa

RESULTS

Maximum crop grouping error is the difference between the average crop coefficient and the coefficient for the crops with highest or lowest coefficient of crops within the group. The coefficients of each crop are time variable and the crop having the highest or lowest coefficients may change during the season. For example, in a crop group including peas and beans, peas will have the highest coefficient in early season, but beans will become higher during mid-summer (figure 13). Maximum, minimum, and average crop coefficient curves for the selected crop groups are shown in figures 14 through 21. Abrupt changes in maximum or minimum curves occur at transitions between crops.

Errors in calculated actual ET are the product of the crop grouping error times reference ET. The effects of grouping error on ET is there fore weighted, depending upon time of year, by the magnitude of

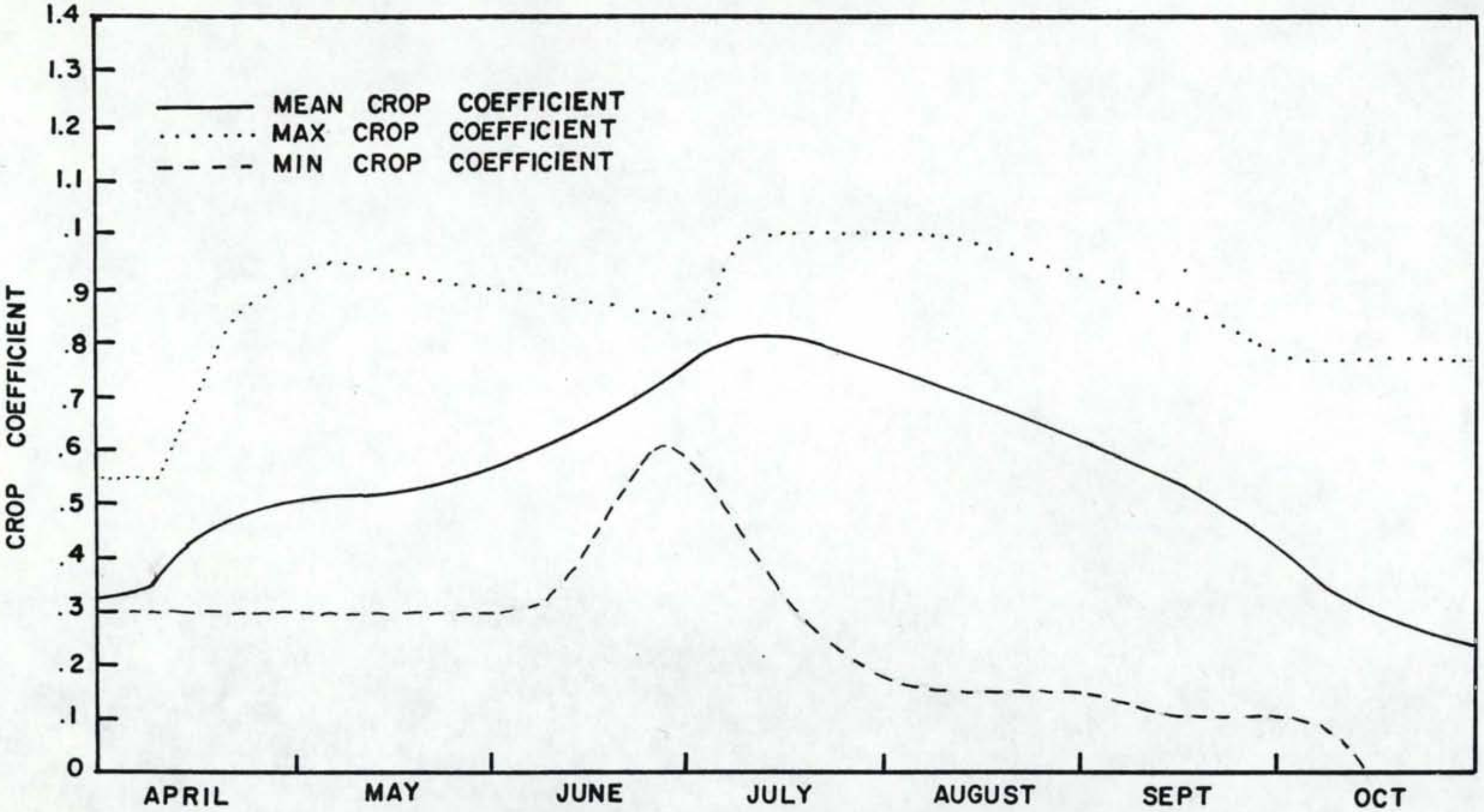

Figure 14. Crop coefficient curves for crop group 1.

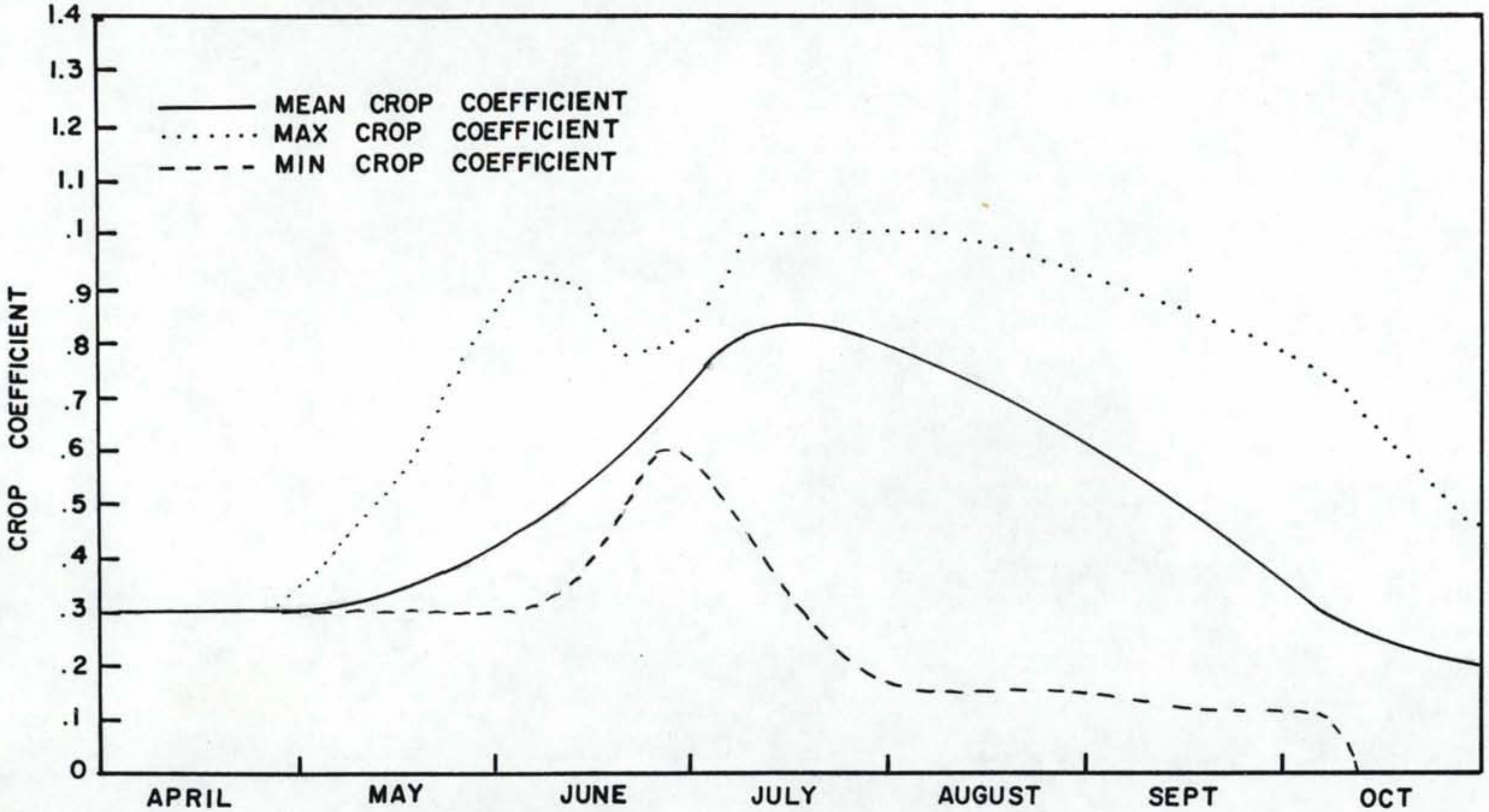

Figure 15. Crop coefficient curves for crop group 2.

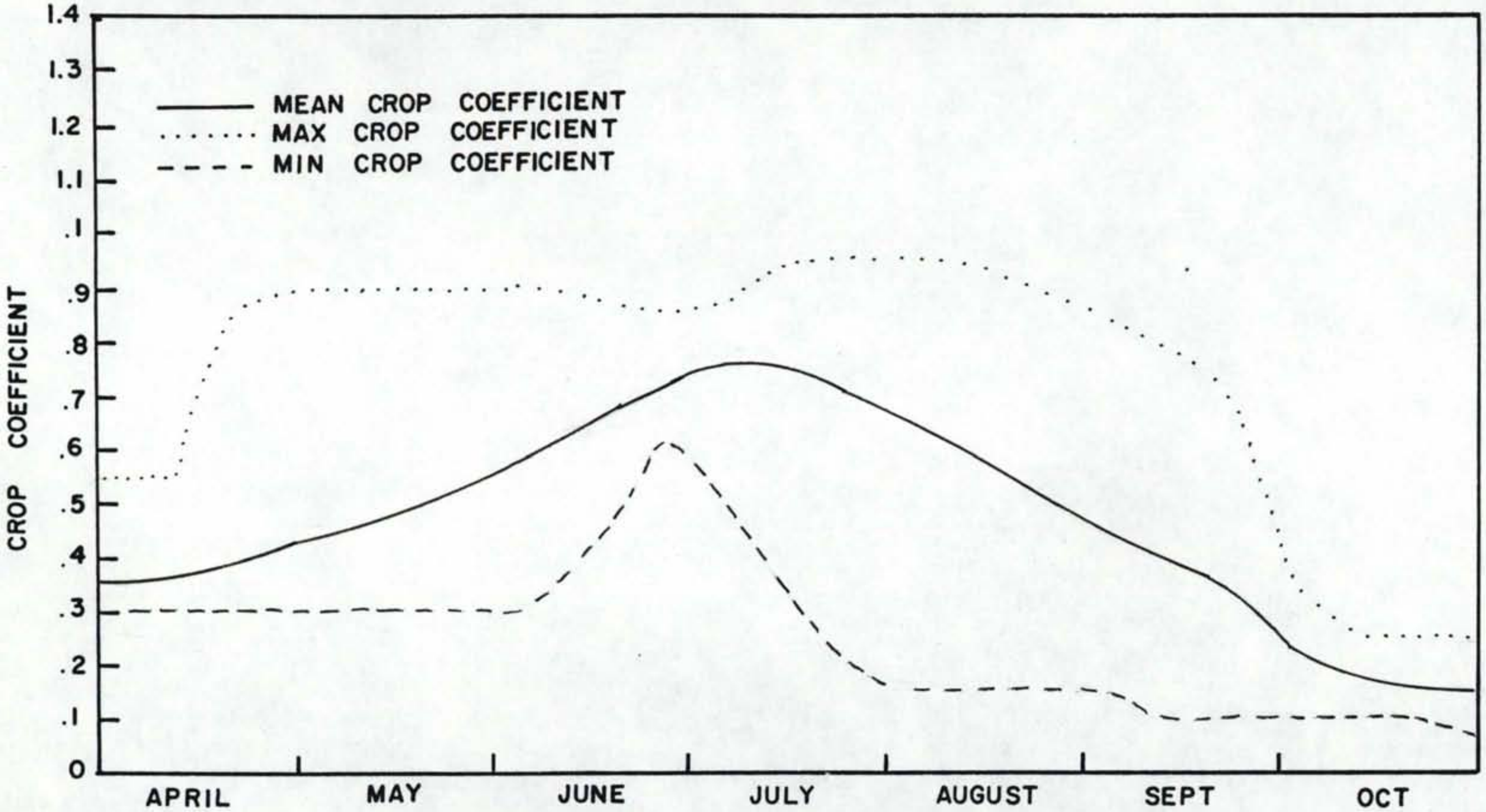

Figure 16. Crop coefficient curves for crop group 3.

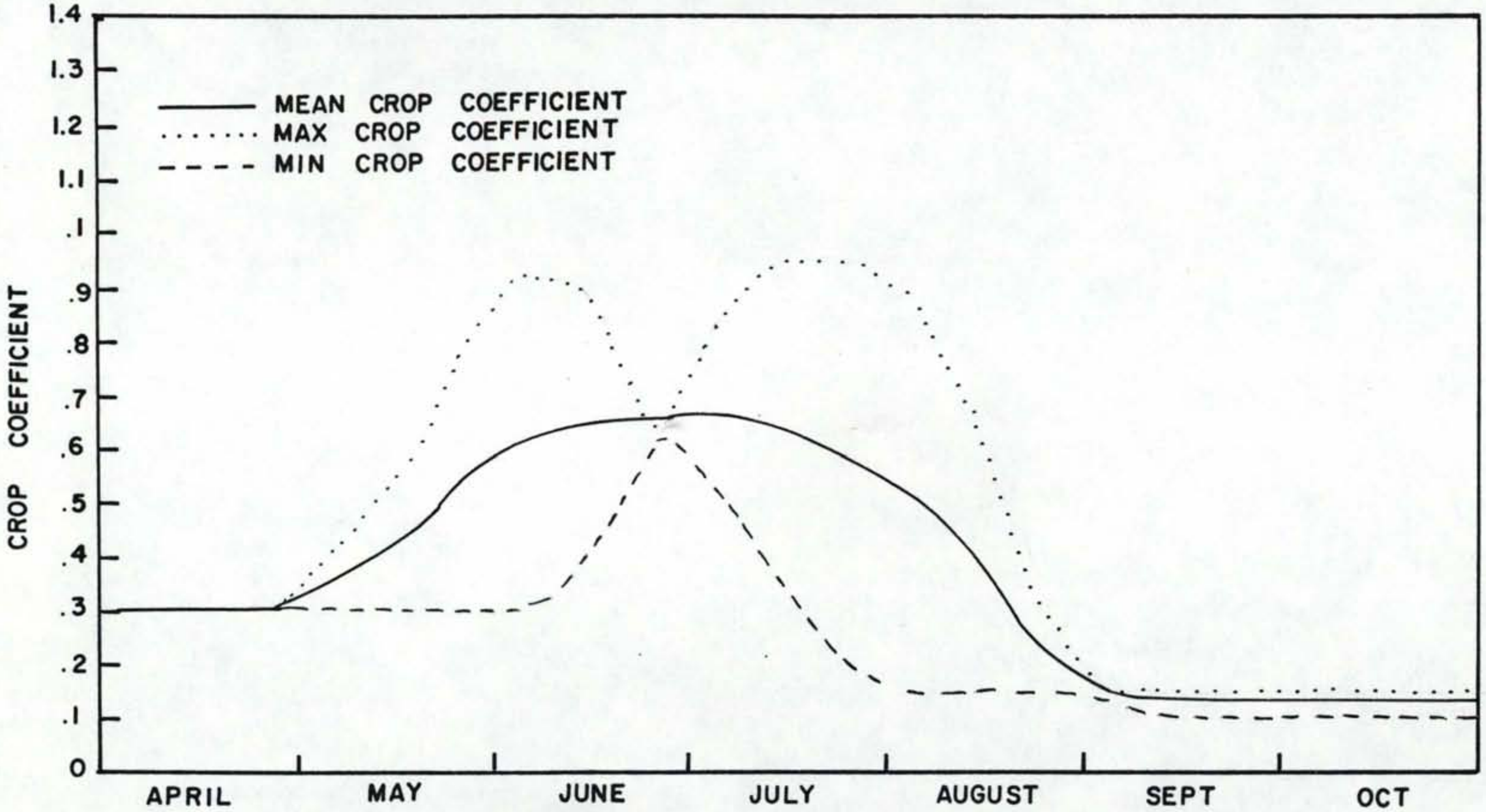

Figure 17. Crop coefficient curves for crop group 4.

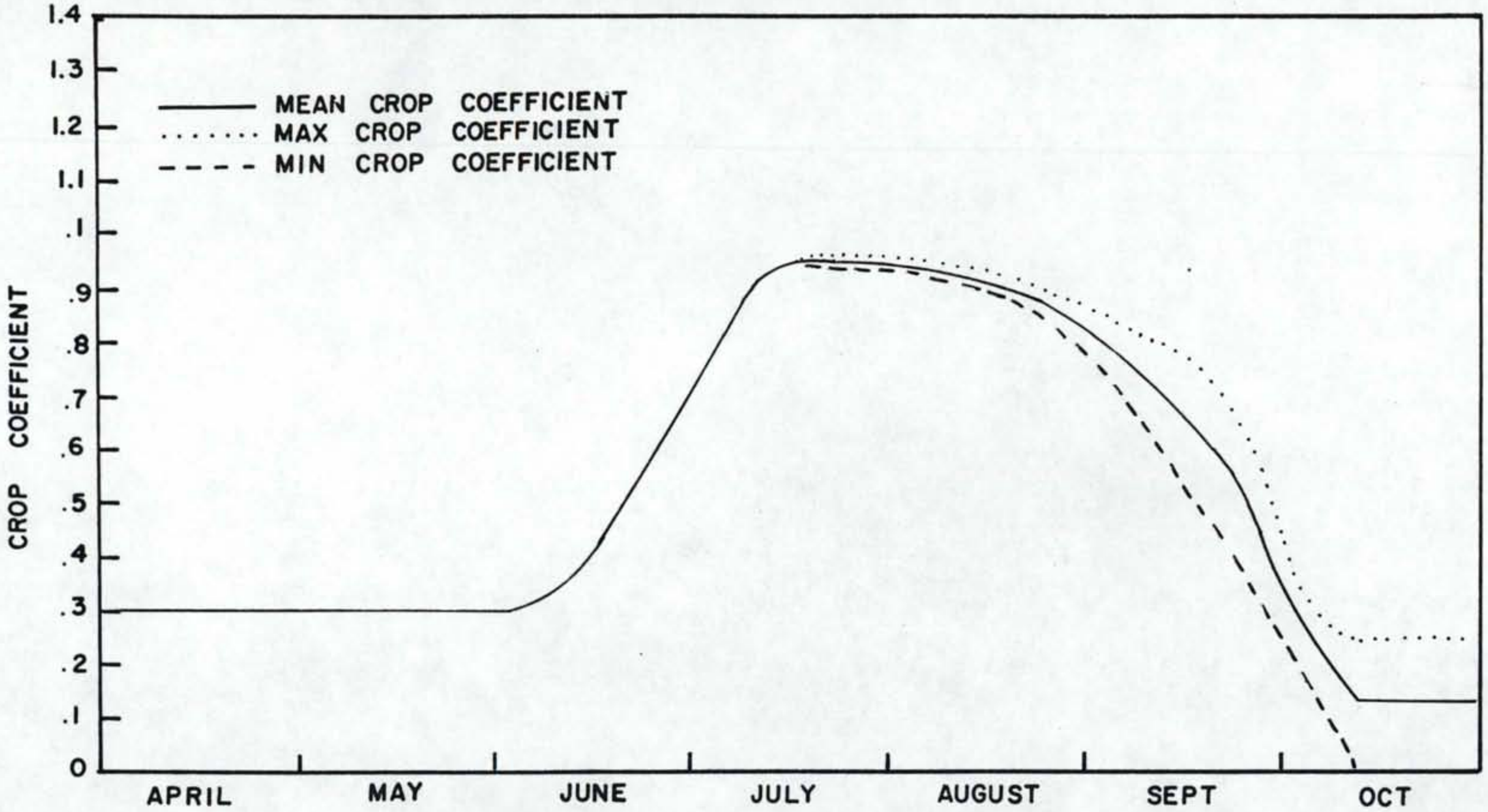

Figure 18. Crop coefficient curves for crop group 5.

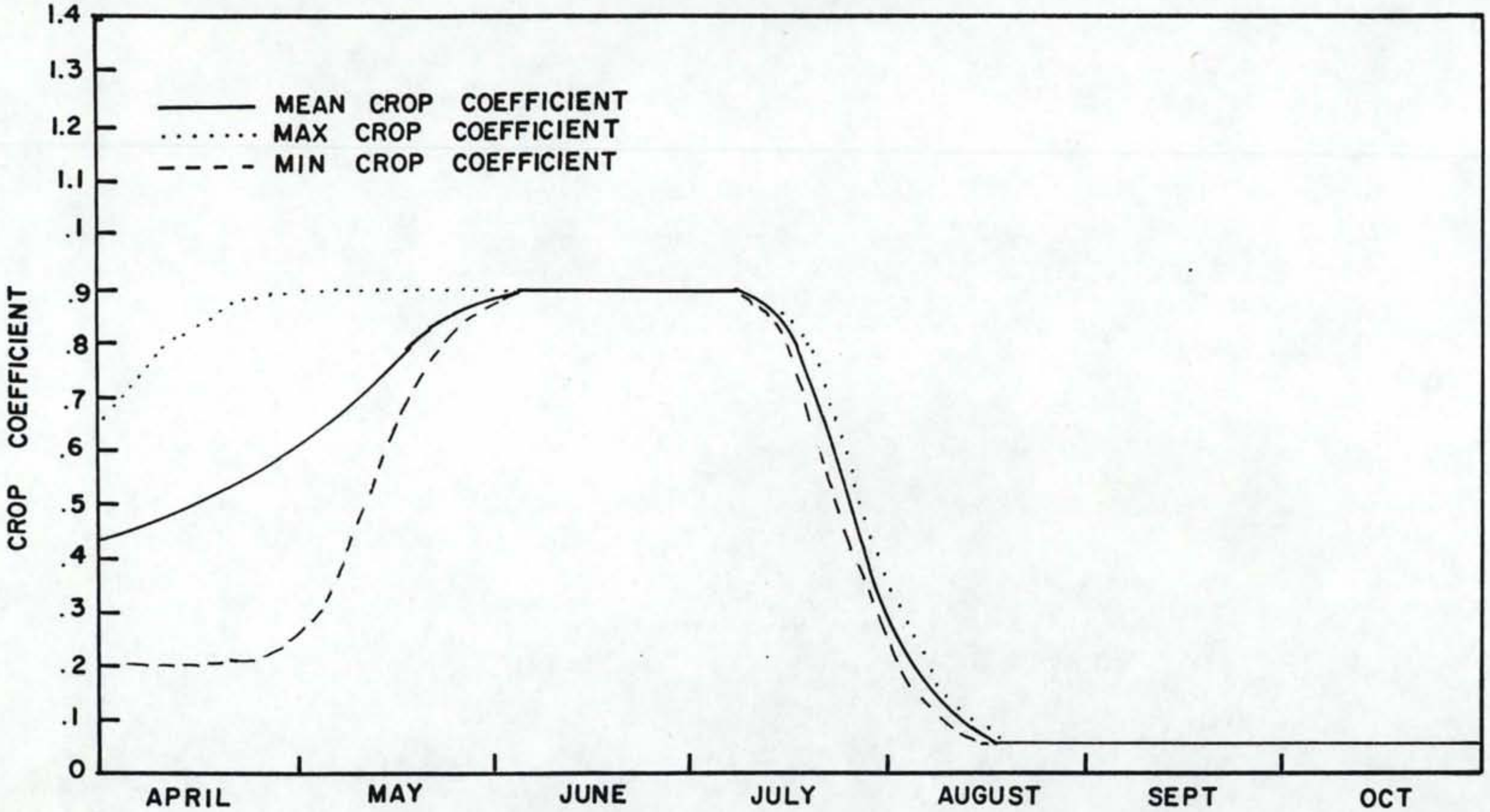

Figure 19. Crop coefficient curves for crop group 6.

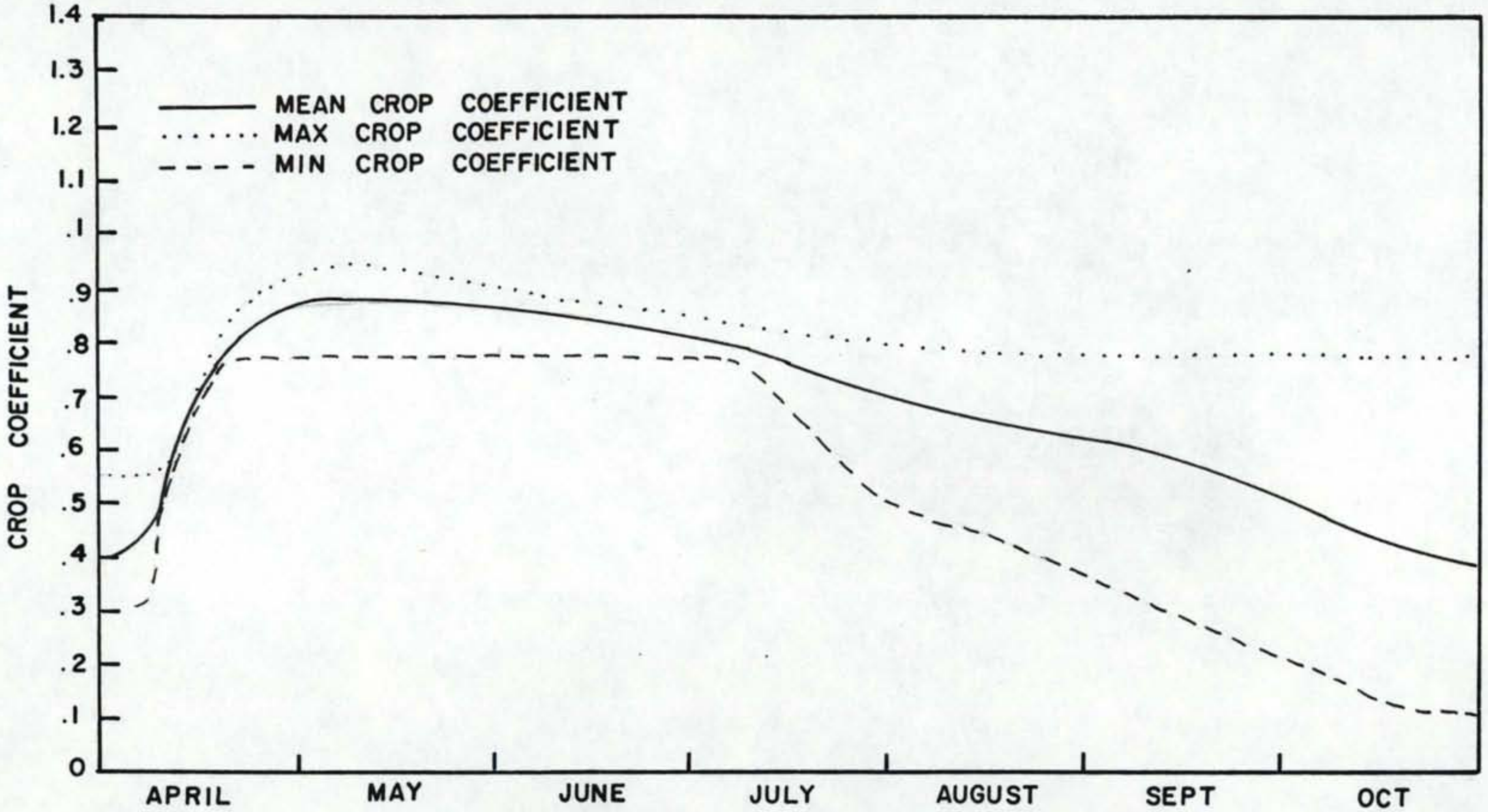

Figure 20. Crop coefficient curves for crop group 7.

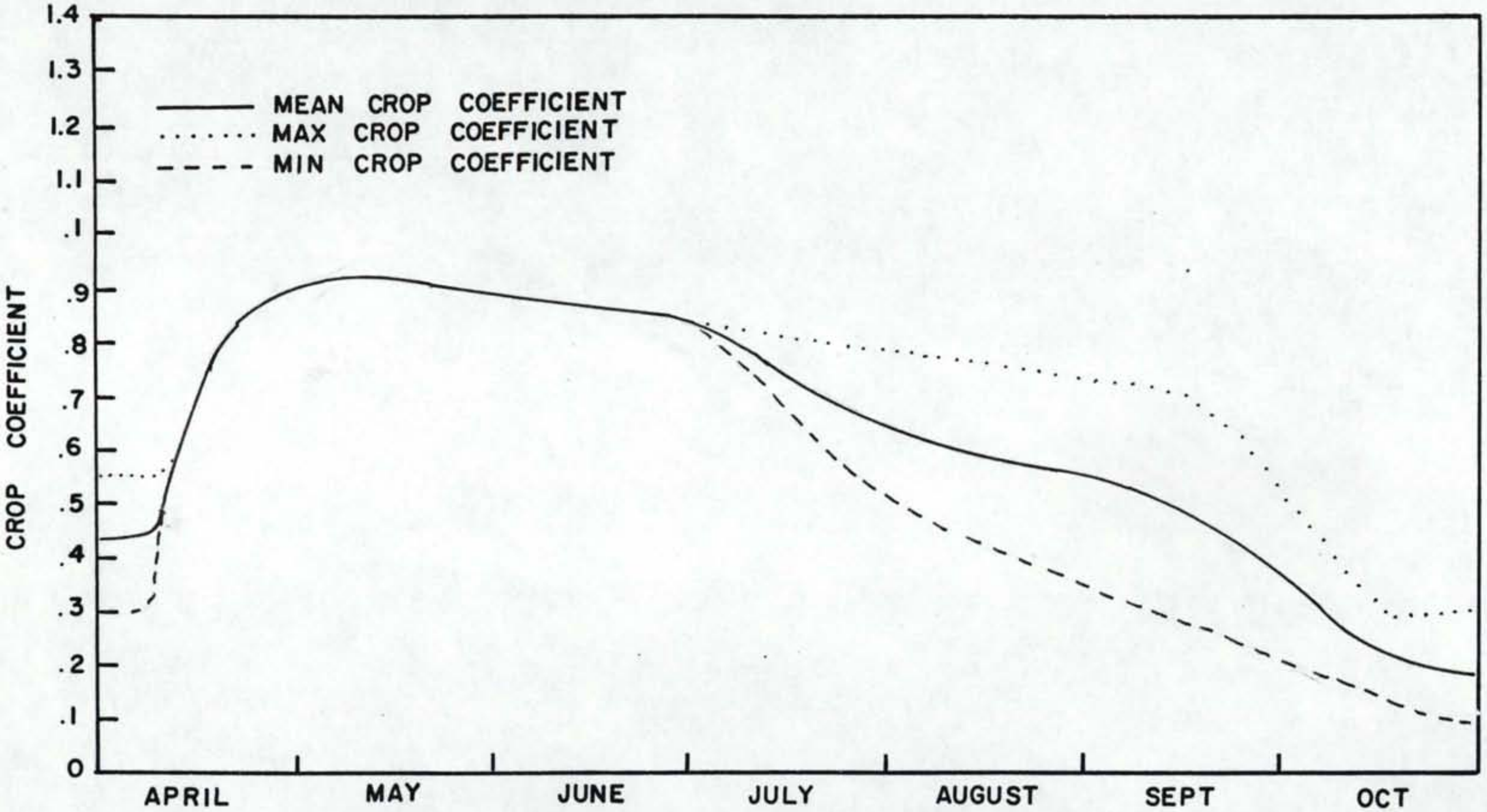

Figure 21. Crop coefficient curves for crop group 8.

reference ET. Grouping errors during mid-summer therefore cause larger differences in estimated ET than errors during times of lower reference ET. Estimated actual ET, corresponding to the maximum, minimum, and average crop curves for each group, are presented in Figures 22 through 29.

Total seasonal error is not directly attainable from Figures 22 through 29. The maximum seasonal error is not necessarily the sum of daily errors since the maximum and minimum ET curves may be a composite of several crops. Maximum daily error may be due to different crops at different times of the year, yet relative percentages of crop areas remain constant. Representing an area of 100% sugar beets by a crop group consisting of all row crops results in maximum daily errors only during late summer when sugar beets have the greatest transpiration of any crop in the group. The total seasonal error, therefore, is less than the sum of the maximum daily errors despite the fact that it represents a worst case situation. Summing maximum daily errors throughout the season implies the area consists of 100% peas during spring, 100% beans in mid-summer, and 100% sugar beets in late summer, which is not possible. Maximum seasonal ET error is the difference between season total ET for the highest or lowest ET crop within a group and the group average ET. Total season ET extremes and averages are given for each group in table 6. Table 6 shows that if the remote sensing technique can only discriminate within broad crop groups (i.e., 1, 2, & 3), the maximum possible error in seasonal ET estimation due to grouping may be from 13 to 35%. However, if the discrimination will allow more definitive crop groupings i.e., groups 4 through 8), then maximum probable errors in seasonal ET of 4 to 13% may be achieved.

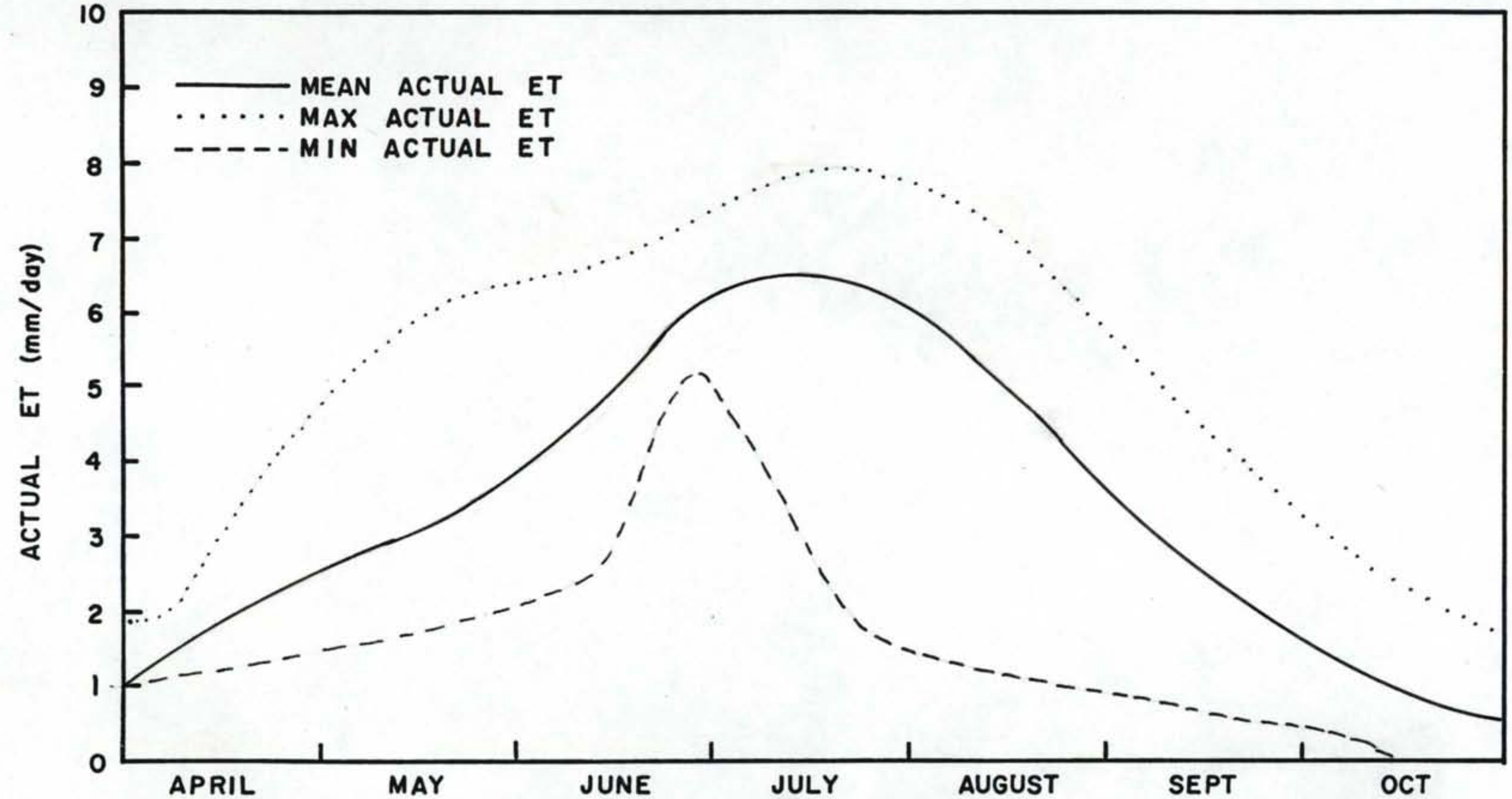

Figure 22. Actual evapotranspiration for crop group 1.

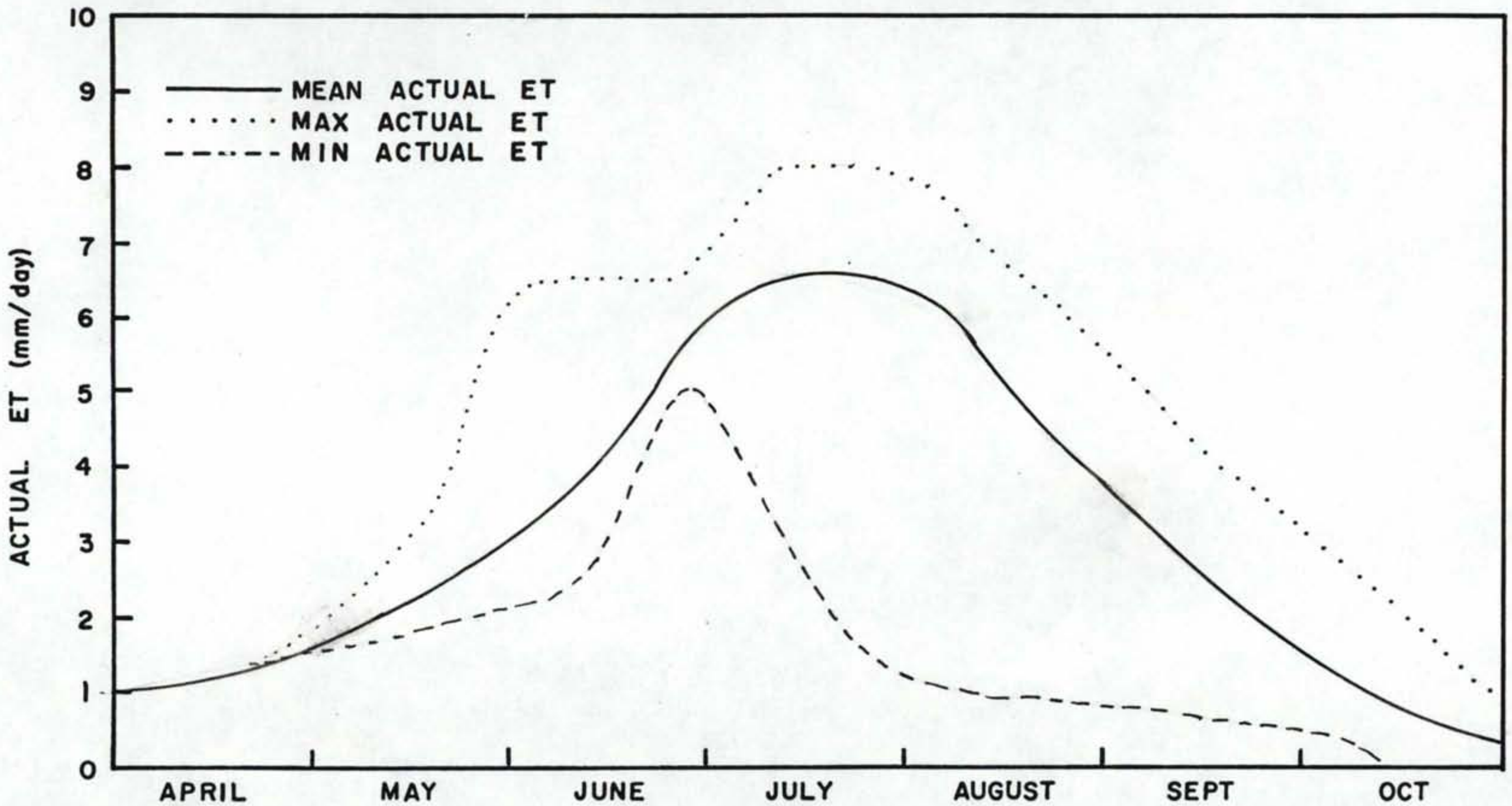

Figure 23. Actual evapotranspiration for crop group 2.

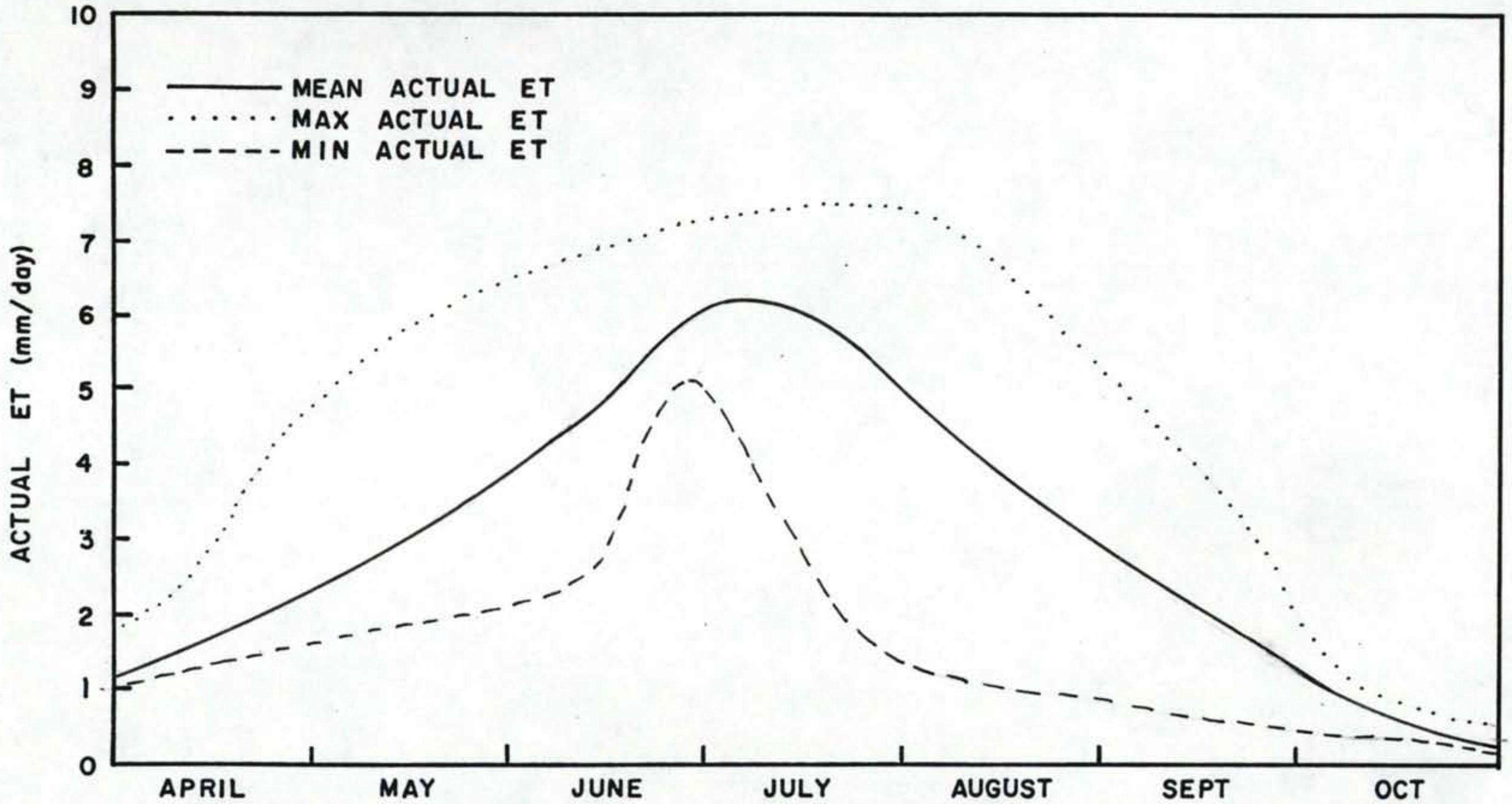

Figure 24. Actual evapotranspiration for crop group 3.

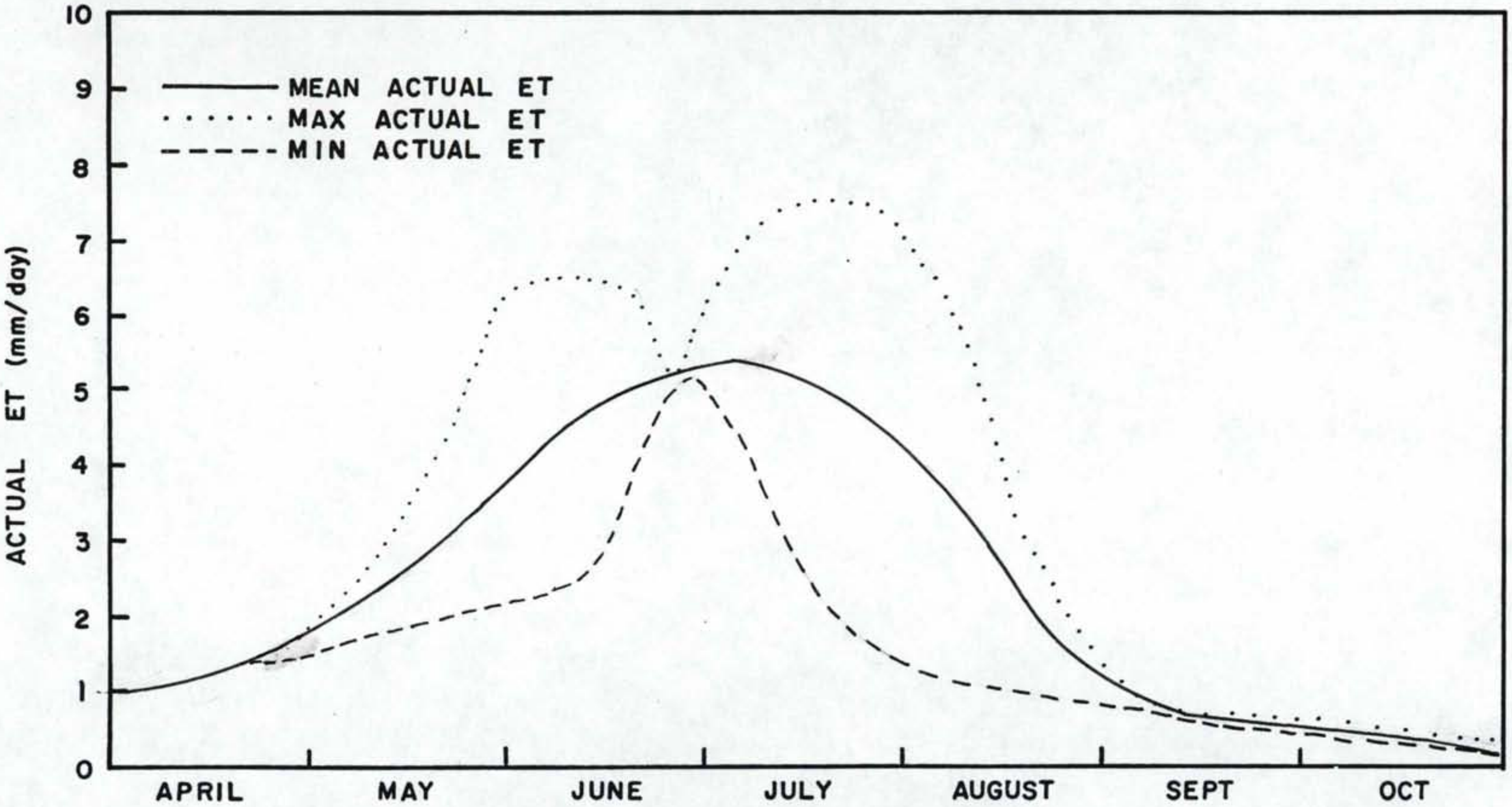

Figure 25. Actual evapotranspiration for crop group 4.

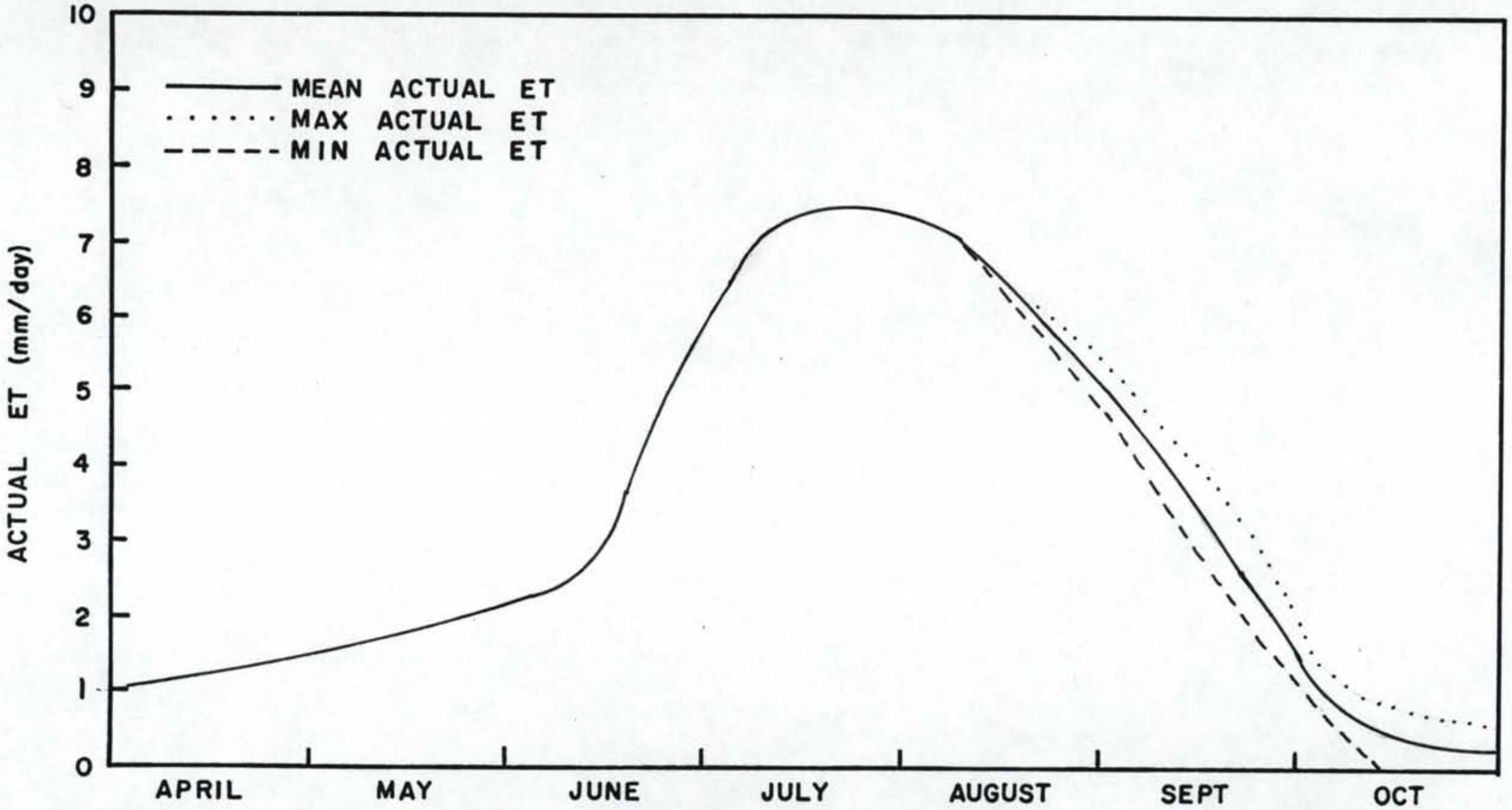

Figure 26. Actual evapotranspiration for crop group 5.

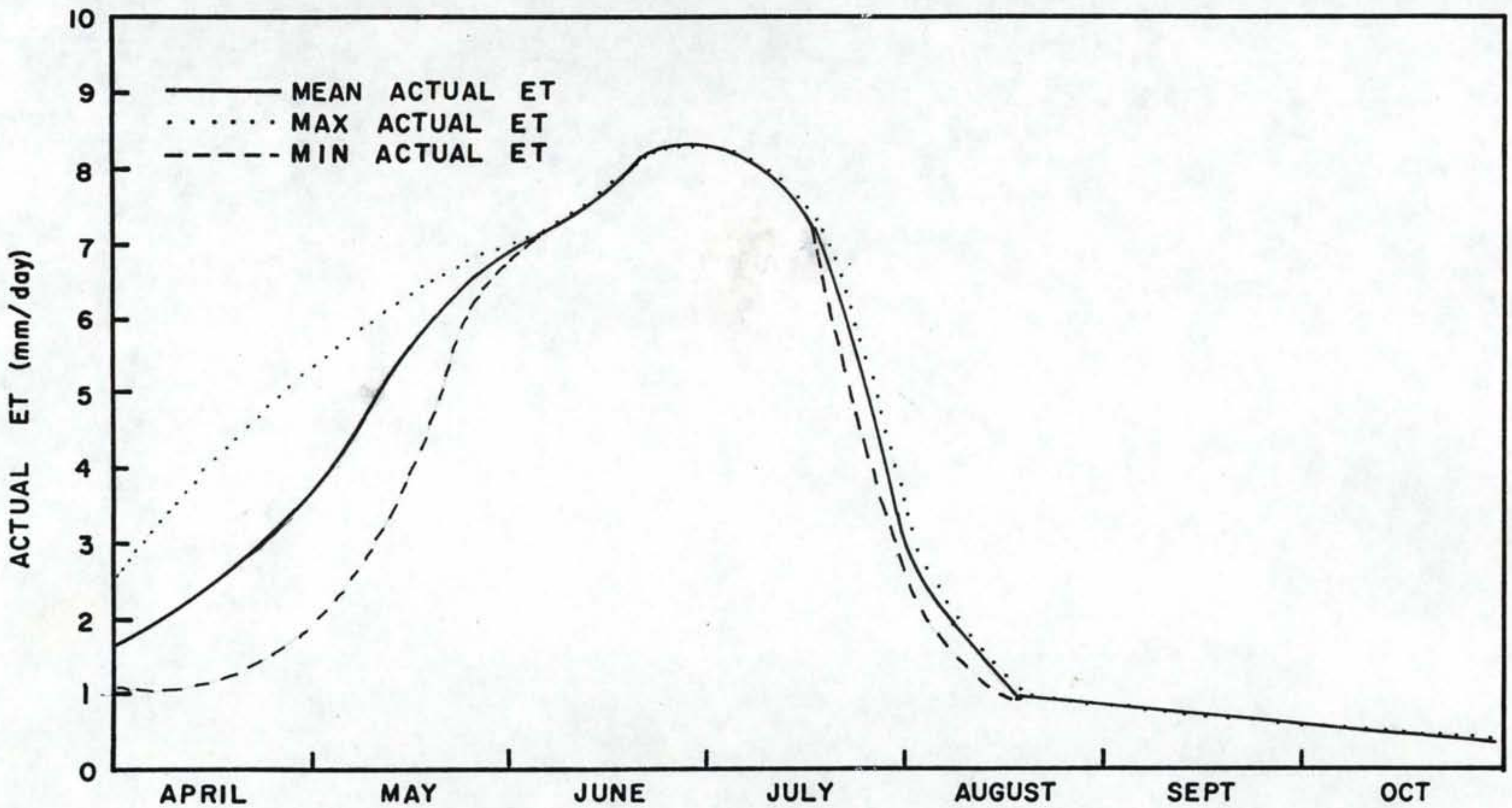

Figure 27. Actual evapotranspiration for crop group 6.

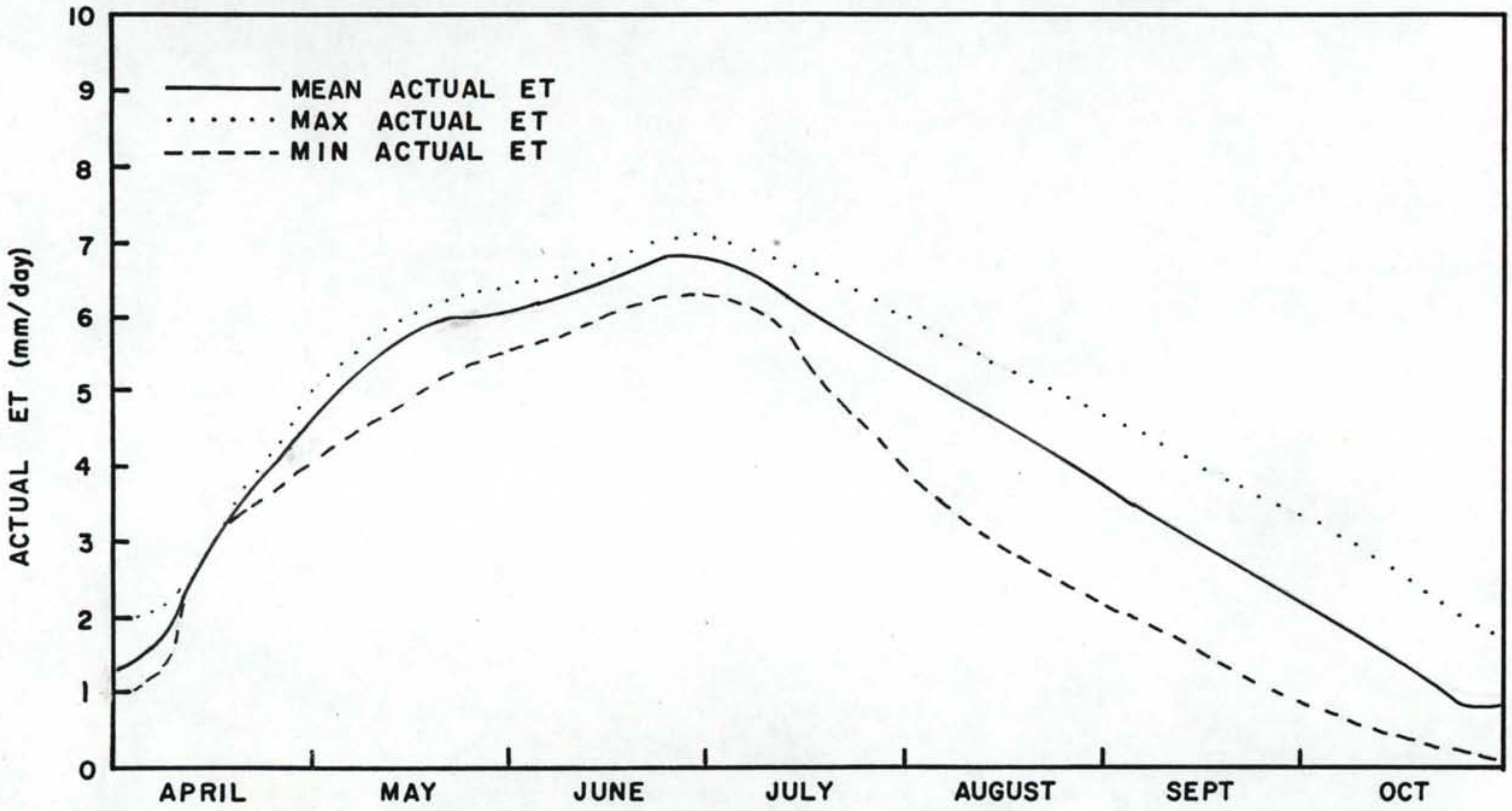

Figure 28. Actual evapotranspiration for crop group 7.

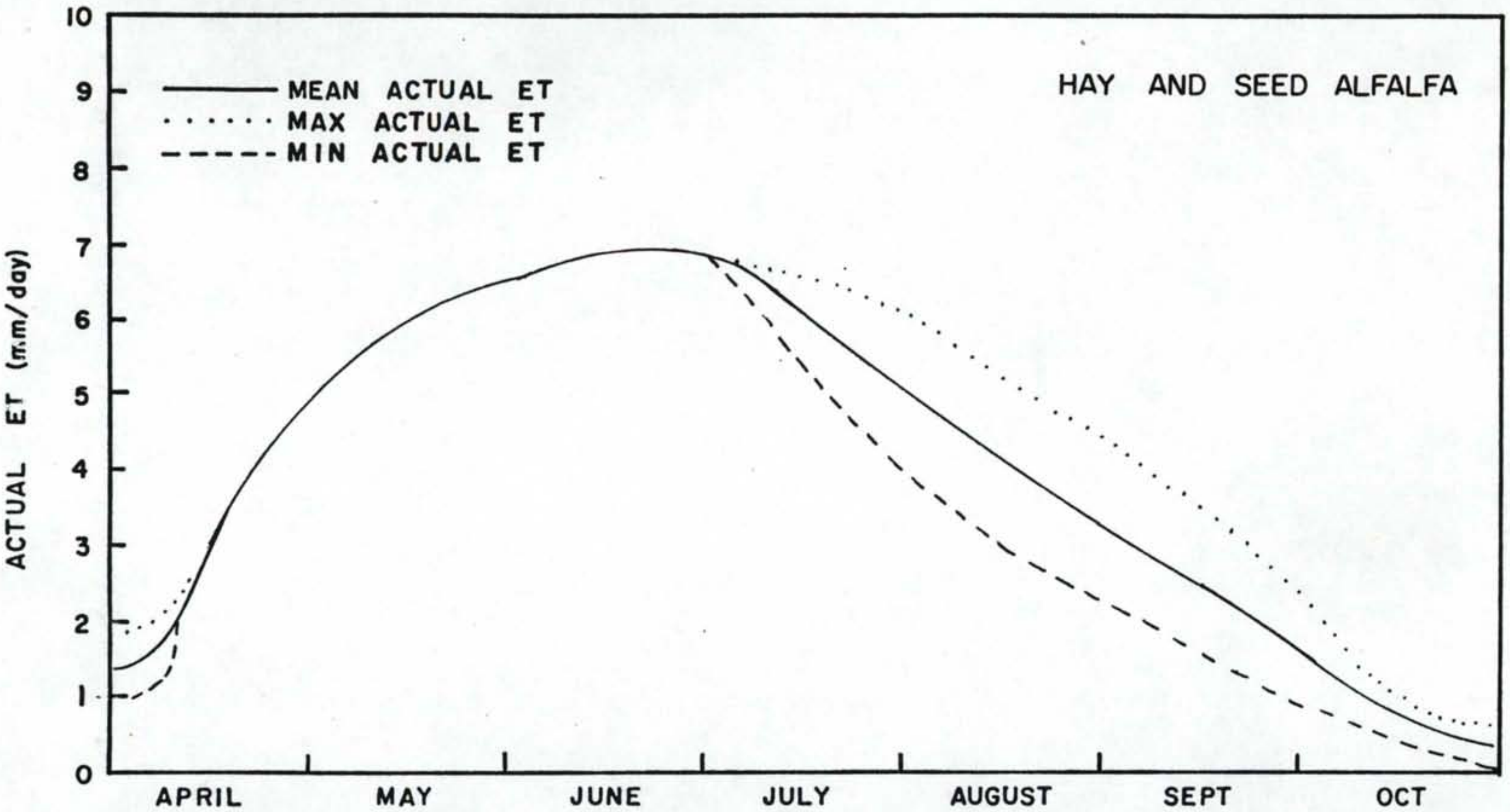

Figure 29. Actual evapotranspiration for crop group 8

Table 6. Maximum seasonal ET differences.

Crop Group	Average ET (mm)	Maximum Crop	Maximum ET (mm)	Maximum Difference[1] (mm)	Maximum Difference[1] (%)	Minimum Crop	Minimum ET (mm)	Minimum Difference[2] (mm)	Minimum Difference[2] (%)
1 Green Crops	756	Alfalfa Hay	962	206	27	Peas	490	266	35
2 Row Crops I	686	Sugar Beets	852	166	24	Peas	490	196	29
3 Row Crops II	670	Field Corn	757	87	13	Peas	490	180	27
4 Beans and Peas	532	Beans	575	43	8	Peas	490	42	8
5 Corn	725	Field Corn	757	32	4	Sweet Corn	693	32	4
6 Small Grains	760	Winter Wheat	814	54	7	Spring Barley	705	55	7
7 Alfalfa and grass	897	Grass Pasture	962	65	7	Seed Alfalfa	780	117	13
8 Alfalfa	870	Alfalfa Hay	962	92	11	Seed Alfalfa	780	90	11

[1] Maximum minus group average.

[2] Group average minus minimum.

RELATIONSHIP BETWEEN CROP BIOMASS/LEAF AREA AND CONSUMPTIVE WATER USE

PURPOSE AND OBJECTIVES

The purpose of this task was to bring together existing research information to help solve the question of whether remote sensing data might enhance the development of practical, regional evapotranspiration models. Data were analyzed on the relationships between crop evapotranspiration (ET) and the amount of crop material present which might be remotely sensed in some way. Base measurements involving such vegetation parameters as crop type, dry matter yield, and leaf area were investigated. For these purposes, crop ET is essentially equivalent to the term "consumptive water use" (CU) and dry matter is equivalent to "biomass".

The general concepts of the relationships between crop ET and crop, soil, and climatic conditions are next reviewed for general background of terminology and concepts. Specific results are presented showing the relationship of the amount of crop material to the intensity of crop ET and accumulated seasonal crop ET.

BACKGROUND INFORMATION

Daily crop ET data collected with weighing lysimeters at Kimberly, Idaho (Wright, 1981, 1982) and other research sites, have shown that for most crops, relative ET increases as crop growth increases from the time of crop emergence until crop cover reaches a certain threshold level, termed effective full cover (EFC). Relative crop ET then stabilizes, even though growth of the plants usually continues beyond the point of EFC until the crop begins to mature, is harvested, or undergoes major structural changes, such as caused by lodging. Total crop ET consists mostly of transpiration (TP) from leaf surfaces, thus the relative amount of leaf area (LA), frequently represented by the leaf area index (LAI), is an important parameter in considering the relationship of ET to crop growth. The relationship of relative ET to LAI explicitly identifies the point of effective full cover.

ET via Remote Sensing

Hatfield (1983) discussed the state-of-the-art of remote sensing methods in estimating ET. His review indicated that it should be possible to measure the amount of crop material present at the earth's surface by one or several methods involving visible and near-infrared reflectances and the ratio of various of the spectral parameters. Some results indicate that remotely-sensed estimates of crop LAI are possible and could be used with ET models to estimate crop ET for purposes such as irrigation scheduling. Other work also suggests that it is possible to relate remotely-sensed parameters to the accumulated dry matter of a crop, during certain periods of growth. A type of vegetative index could relate sensible crop parameters to the crop dry matter and possibly provide a link to usable ET models. Green leaf area and green leaf biomass have been correlated to spectral data. Hatfield concluded that there is potential utility "...in the use of crop spectral reflectance data to assess LAI (or crop cover) which could be directly applied to evapotranspiration models."

Hatfield also discussed the use of spectral measurements to detect crop-water stress, which is of fundamental importance in being able to determine relative evapotranspiration. He showed that it should be possible to relate the ET crop coefficient, at least for some crops, to a relative vegetative index. He felt that if such relationships could be developed for a number of crops, then it might be possible to utilize remotely sensible parameters to estimate crop coefficients over large regions. Parameters of most importance would be those concerning the degree of plant cover and the variation of growth within a region.

Measurements of Crop Growth

The term, leaf area index (LAI), has been used since first proposed in about 1947 by Watson (1952) to describe the leaf area (LA) of a crop on the same basis as yield; that is, as the area of leaf surface per unit area of land surface. (The leaf surface applies to one side only of the leaves.) The term has been especially useful in comparing the growth of different species of crops. Several such comparisons have been reported for various crops and LAI has been related to crop type, plant spacing, and management practices (Watson, 1952; Donald, 1963; Wallace, et al., 1972; Evans and Wardlaw, 1976; to name a few).

The change in the LAI of developing plants can generally be categorized into four phases of crop growth. In the initial phase, the young plant following emergence typically has low and slowly increasing leaf area as it becomes established. During the second phase, the leaf expansion per plant is rapid, nearly exponential with time, so that the total LAI (including the ground area between plants) increases nearly linearly with time until the third phase, or maximum LAI, is achieved. The third phase may be relatively short or long in nature depending on the plant type. It is short for the small grains, and long for crops like sugar beets. During the third phase, older leaves may senesce due to shading, insect damage, or disease, to be replaced by newer leaves. This phase is usually associated with the physiologically reproductive stage of growth when much of the plant energy is going into reproductive organs or other storage tissue. The fourth, and final phase, is one of declining leaf area and is usually associated with maturation of the crop, but also may be climatically induced such as by a frost.

Genetic factors control the main differences between crops, their growth habit and leaf area development. The LAI of a crop can be highly variable, even for a given variety, within a region on any given year. Yearly differences may also be pronounced. This is so because the development of leaves by a plant is strongly influenced by physiological growth conditions, or what might be called external factors, as well as the internal genetic factors. Soil fertility, water availability, light intensity, temperature and other climatic factors, and diseases, and insects all have some influence on leaf area development.

In the early stages of growth, the transpiration component of ET is largely a function of the extent of leaf area. As the leaf area increases so does the transpiration, until energy exchange and diffusion processes become the limiting factors, which normally occurs at the time of canopy closing, or the point at which the ground surface is mostly shaded within and between rows of a crop. Once the canopy is closed, further increases in LAI have little effect on transpiration rates. However, the structure of the crop at canopy closing does have some influence on crop ET. This is partly because of the effects of leaf orientation on light interception, and the effects of crop morphology on the aerodynamic exchange of heat and water vapor between the crop canopy and the atmospheric-surface-air-layer.

The net growth of a crop is typically measured in terms of the yield of plant material at a given stage of growth. Since water is the major portion of living plant material, and since water contents are highly variable depending on genetic and environmental factors, yield is usually expressed on a dry weight basis. This may be an oven dry weight or an air dry weight, depending on the method and purpose of analysis.

Accounting for the variation in yield between different species of crops, and even between crops of the same species, is very complex. The net growth of the plant, particularly the net accumulation of plant dry matter with time, involves many of the same factors which affect the development of leaf area, such as genetic factors and all of the external factors which affect the physiological processes of the plant.

Photosynthesis provides most of the increase in crop dry weight, as well as the energy to drive the metabolic processes of growth. Factors favoring optimum photosynthesis are often those which favor relatively high plant transpiration, such as ample sunlight, warm temperatures, rapid diffusion and turbulent gaseous exchange within the plant environment, readily available water within the soil root zone, and adequate nutrient availability, all promoting rapid expansion of leaf and other plant organs. Consequently, agronomic practices favoring highly productive crop growth also lead to relatively high ET rates. Crop water use is related to plant growth but in a very complex manner.

For purposes of this study, the plant growth factors of greatest importance are those which affect the spectral reflectance and/or emission of thermal and radiant energy from the composite crop canopy. The crop leaf area has a major impact on this as does also the total plant dry matter accounted for in the leaves, stems, fruiting organs and other above-ground portions of the plant. In early growth phases a large portion of the plant dry matter is in the leaves whereas in latter phases only a small portion may be. Important morphological characteristics of the crop, as to remote sensing, are leaf size and number, the position, angle, and vertical and horizontal distribution of the leaves, total plant height, the within and between row coverage of the soil surface, and the presence of reproductive organs such as tassels, ears, pods, heads of grain, etc.

Plants, and particularly those of common agronomic crops, more or less continuously increase in size and develop new organs, at least intermittently, throughout their life history. While the simplest connotation of growth is that of an increase in plant size, it is, of course, only one feature of the growth process. Nonetheless, although plant physiologists frequently use growth in specific senses, the term growth can be used to include the increase in size as well as the formation and development of new organs.

The development of the plant-root-system closely parallels the growth of the above-ground portions of the plant. The dry matter in the plant root system may be of the same order of magnitude as the above-ground plant material. With some crops, such as potatoes, sugar beets, carrots, etc., once the above-ground leaf area is established, the below-ground dry matter accumulation exceeds that of the above-ground portions. Nonetheless, even these plants must maintain relatively high leaf areas for optimum photosynthesis. Of course, only the above-ground portions of the plant will have an effect on remote sensing measurements. Root crops usually have relatively less stem and other vegetative material above-ground than do crops with above-ground fruiting bodies.

Estimating Crop Evapotranspiration Using ET Crop Coefficients

The use of crop coefficients to estimate crop ET was briefly discussed in an earlier section of this report. An expanded discussion is presented here as a background for the manner in which crop ET was determined for comparison with crop growth.

The derivation and use of the general ET crop coefficient are given by two equations:

$$KC = ETC/ETR \quad (1)$$

$$ETC = KC*ETR \quad (2)$$

where KC is the dimensionless ET crop coefficient for a particular crop at a given growth stage and for given soil moisture conditions, ETC is daily crop ET (mm/day), ETR is daily reference ET (mm/day), and * signifies multiplication. Crop ET is dependent on the extent to which the crop canopy shades the soil, on the degree to which available soil moisture supports transpiration, and on the rate of evaporation directly from the soil, which is largely dependent upon surface wetness. The crop coefficient can be factored as:

$$KC = KCB*KA + KS \qquad (3)$$

where KCB is a basal crop coefficient (Wright, 1982), and KA and KS are coefficients related to available soil water and surface soil wetness, respectively. Various algorithms may be used to represent KA and KS. Only limited data are yet available on these relationships.

A form of Eq. (3) which combines the effects represented by KS is:

$$KC = KA*KCM \qquad (4)$$

where KM is a mean crop coefficient including effects of a wet soil surface. Values of KCM are derived when KA = 1 so that KC = KCM.

Crop coefficients are empirically derived from experimental data using Eq. (1) while Eq. (2) is used to estimate crop ET when previously derived crop coefficients are available. The distribution of KC with time throughout the season forms an "ET crop coefficient curve." Relations between KC, KCM, KCB, KS, and KA are shown diagramatically in figure 30. The basal crop coefficient curve, KCB, represents conditions when the soil surface is visually dry, so that soil evaporation is minimal, but soil water is sufficiently available to support maximum plant growth and transpiration. Some basal coefficients have been

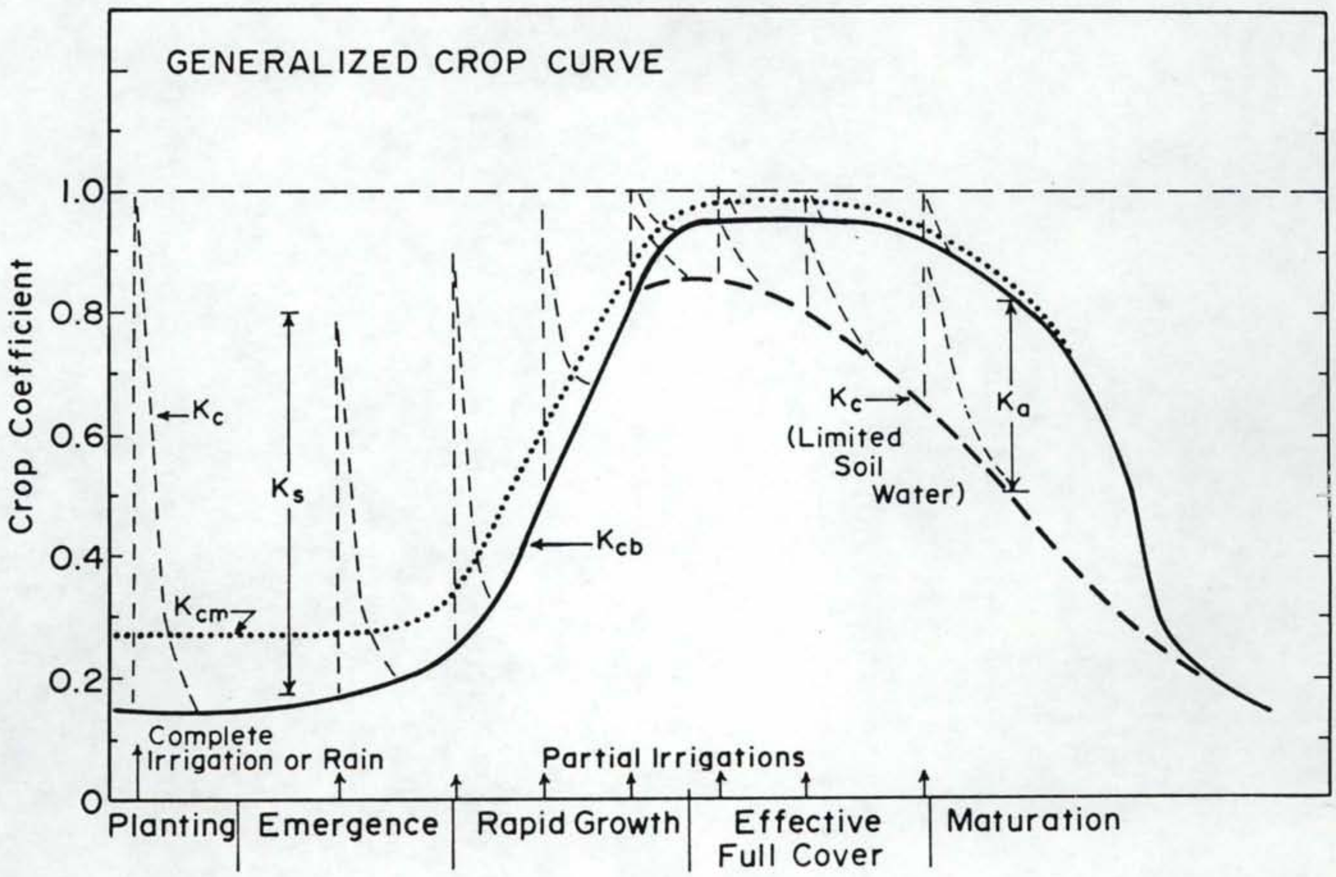

Figure 30. Generalization of the basal (K_{cb}) and mean (K_{cm}) ET crop coefficient curves in relation to stage of crop growth and showing the effects of irrigation, precipitation, and limiting soil water (after Wright, 1982).

developed utilizing ET data obtained with weighing lysimeters in southern Idaho and central California (Burman et al. 1980; Wright, 1982). The mean ET crop curve, KCM, includes the effects of rain or irrigation on surface soil wetness and may be more useful than a KCB curve for estimating daily crop ET when it is impractical to assess wet soil effects, or it is necessary to estimate total seasonal water requirements for a general area from historical climatic data and dates of rain or irrigation are not known. The KCM curve lies above the basal curve to various extents, depending on the irrigation and rainfall pattern and soil drying properties. When KCM is used to estimate ETC, adjustment may be made for the effects of limiting soil moisture, Eq. (4), if appropriate KA relationships are available. Mean daily crop coefficients, developed from the same lysimeter ET data as used to derive the basal coefficients, were reported by Wright (1981).

Methods available for estimating ETR for use with Eqs. (1) and (2) depend on data availability and local circumstances (Jensen 1974; Burman et al. 1980, 1983; Doorenbos and Pruitt 1977) and were discussed under "Sensitivity of ET Estimating Methods". The Penman combination approach is recommended where sufficient data are available. Methods based solely on temperature are generally inadequate for arid or semiarid regions. It is important when estimating ETC by Eq. (2) to use the same type of ETR as was used in the derivation of the crop curve.

Alfalfa reference ET, ETR, has been used for arid climates (Jensen et al. 1971; Wright and Jensen 1972, 1978; Wright 1981, 1982) and is defined as the daily ET of an actively growing alfalfa crop covering an extensive area, at least 30 cm tall and standing erect, and well watered so that soil water availability does not limit ET. Wright and Jensen (1972) used lysimeter data and a modified Penman combination equation to develop procedures for estimating alfalfa ETR from meteorological data. Wright (1982) later modified these procedures to further account for seasonal variability.

Grass reference ET, frequently denoted as ETO, has also been used and is defined as the ET of well-watered, actively growing, green grass which is clipped to a uniform height of 8-15 cm, completely shading the soil, not short of water, and covering an extensive area (Doorenbos and Pruitt 1977). Short grass ET is less than alfalfa ET. Thus, when ETO is used in place of ETR in Eq. (1), the crop coefficients derived for a given crop are larger than when ETR is used.

Because of its interactions with the energy exchange and mass transfer processes operating within the atmosphere over a field, ETR is affected by the nature of the crop canopy and general topographical and climatic conditions. Consequently, specific wind functions representing local conditions should be used with the combination equation for the most satisfactory results (Slatyer and McIlroy 1961). The same procedures should be used in computing the vapor pressure deficit for use with the various wind functions as were used in their derivation (Cuenca and Nicholson 1982).

A project aimed at developing methodology for estimating consumptive irrigation requirements for crops in Idaho on a state-wide basis (Allen and Brockway, 1983) compared four methods of estimating ET from climatic data. The FAO-modified Blaney-Criddle method was selected as the most useful method because of the minimal data requirements and lack of data for some of the other methods. The selected method was used with an adjustment of estimates based on correlations developed at the Kimberly location where lysimeter derived ET and associated meteorological data were available. Monthly statistics were computed for consumptive use estimates for 98 weather sites in Idaho.

Growing Degree Day Computations

The relationship of plant growth to general air temperature conditions is frequently quantified with a growing degree day (GDD) term. Research has shown that different plant species have different threshold temperatures below which, under most conditions, growth does not occur. Some also have upper threshold levels. When temperatures exceed this level, net growth rates are reduced or plant material may even diminish. Detailed data are not available for the upper and lower temperature limits for all crops.

A growing degree day system for Idaho was presented by Everson et al. (1976). They compared new and old ways of computing growing degree days for several locations in the state. With the old method, the growing degree day is computed as the daily mean air temperature minus the base or threshold temperature. With the new method, a daily mean temperature is similarly computed except that the daily minimum and maximum temperatures are set equal to the lower or upper threshold temperatures if they are less than or greater than those levels, respectively. Then the appropriate temperatures are averaged and the base temperature is subtracted.

Daily growing degree day units are normally accumulated for periods of concern to provide accumulative growing degree days. These are then sometimes compared with various measures of crop growth during those periods.

Modeling Crop Growth

In recent years, considerable effort has gone into the development of crop yield models to permit computing crop yield from climatic and other data. One such recent effort by Hill et al. (1985) attempted to adapt crop yield models to irrigation scheduling programs so that the ET crop curve could be related to crop growth rather than a strictly time dependent base. These models used the same input data as normally used to estimate crop ET. Submodels were developed for several of the crops grown in southern Idaho. These were then calibrated, verified, and tested with data obtained in field experiments at Kaysville and Logan, Utah, and Kimberly, Idaho. The agreement between model and field relative yield was good to excellent for calibrated conditions at a given site; however, the match between model and field results deteriorated considerably when the model was tested at locations other than where it was calibrated. It was concluded that the model was not sufficiently inclusive to account for all growth and location factors, limiting its transferability.

The complex growth processes may not yet be sufficiently understood to permit quantifying them for modeling efforts. If this is so, then perhaps there are realistically also some limits as to the possibility of using remotely-sensed crop parameters to model regional ET. While the remote sensing technique holds some promise, there are yet many major problems to be overcome and much basic information is needed on the relationship of crop growth, not only to consumptive water use, but also all other climatic factors.

PROCEDURES

Data were obtained for this analysis in studies of the major crops of southern Idaho during the period 1973 through 1983. The crops were grown on research plots of the USDA, Snake River Conservation Research Center (USDA, SRCRC) about 1 Km east of Kimberly, Idaho, in the south-central portion of the state. Agronomic practices were aimed at obtaining maximum yields for local conditions.

Leaf area (LA) and dry matter yields (DMY) were obtained periodically (about twice monthly) throughout the growing season. During the first years of the study, LA data were obtained by photocopying procedures whereby the leaf samples were copied, the leaf images cut out, the paper was weighed and the LA was calculated using measurements of the surface density of the paper. During the latter portion of the study, an automatic photometric leaf area machine was used for these measurements. The dry matter yields were obtained from samples of all of the above-ground portions of the crop for a given area, drying the samples in large crop-drying ovens at about 60°C, until further water loss was negligible, and then weighing of the dried samples. Thus the DMY's were on an oven-dry-basis.

Daily crop ET (ETC) values for the individual crops were computed using Eq.(2). The appropriate mean ET crop coefficients (KCM) and the mean reference ET (ETR), were used for the several years of the study. The mean ET crop coefficients, KCM, selected were based on the previously reported results of Wright (1982) and were similar to those shown in figure 13, but were extended to cover the entire 7-month period. The selected mean ET crop curves are shown in figure 31, at 5-day intervals throughout the season from 3/31, day 90, through 10/28, day 300. A bare soil KCM of 0.2 was used for April and May to represent average conditions of surface soil wetness prior to the establishment or emergence of the crop. Spring barley and wheat were considered to have similar crop coefficients. For purposes of this study, it was assumed that new alfalfa was seeded with spring grains or that it was seeded immediately after the pea or grain harvest in August. This is frequently the manner in which new alfalfa is seeded in southern Idaho. The KCM values for new alfalfa following peas and spring grain are estimates based on experience and general observations of the growth and development of such crops. Experimentally derived data are not yet available for these situations. Actual lysimeter measurements of crop ET had been used by Wright in the derivations of the mean ET crop coefficients for several of these crops. Thus the calculated ETC values were not far removed from actual field measurements.

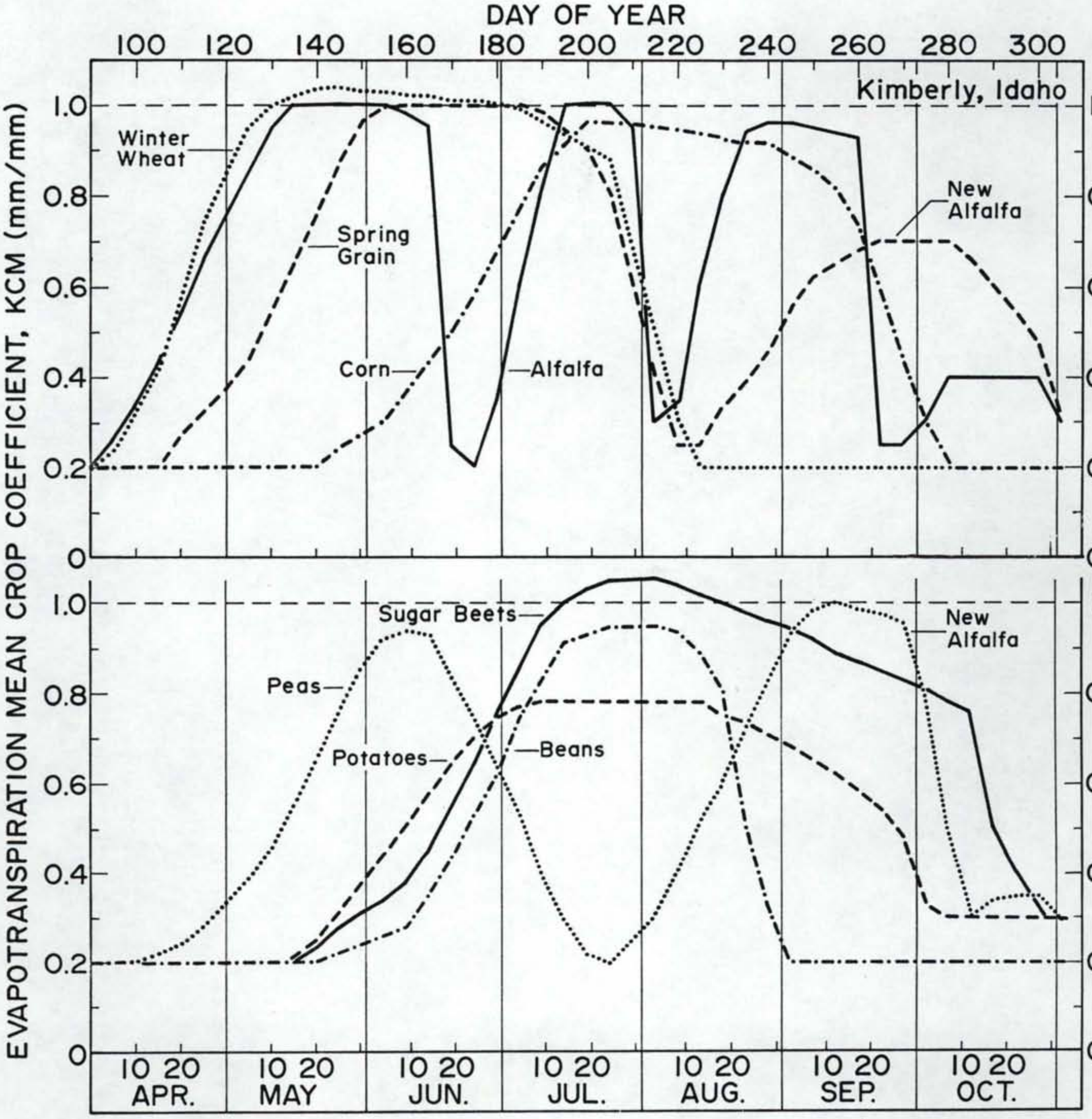

Figure 31. Mean ET crop curves throughout a 7-month season for eight major crops grown in southern Idaho.

Daily alfalfa ETR was computed from meteorological data for each of the years of the study for the growing season, April through October using the specific procedures of Wright (1982) for the modified Penman equation. These computations were similar to, but independent of those mentioned in earlier sections of this report and referred to as Wright 82. The required meteorological data consisted of maximum and minimum air temperatures, 0800-hour dewpoint-temperature, 24-hour wind travel and solar radiation. These data were obtained at the NOAA, National Weather Service (NWS) Station located at the USDA, SRCRC. A mean curve of daily ETR for the period 1973 through 1983 was developed from the computed daily values for the individual years. The mean curve was then used in the computation of daily ETC for the individual crops providing smoothed average crop ET for comparison with the smoothed crop growth data.

Results and Discussion

The crops selected for the presentation of LAI, and DMY, are LISTED in Table 7 along with information on the year the crop was grown, observed planting dates, and dates of crop emergence and harvest. The established (est.) alfalfa was seeded in 1980, thus the stand was 4 years old at the time of the measurements in 1983. The alfalfa began growth about 04/01, after winter dormancy, and returned to dormancy about 11/01. The winter wheat crops were seeded in the fall of one year and harvested during the summer of the following year. The young winter wheat seedlings were generally dormant from mid-November through the end of February. Beans and peas refer to crops raised to maturity for seed production, as is common in southern Idaho.

Table 7. Tabulation of crops and years for which leaf area index and dry matter yields were obtained, Kimberly, Idaho.

Crop No.	Crop	Year	Date of Planting	Date of Emergence	Date of Harvest
1	Alfalfa,	1983	4/01[1]	-	
	Est. 1st cutting				6/16
	2nd cutting		-	-	8/02
	3rd cutting				9/22
	Dormancy		-	-	11/01
2	Spring Grain				
2	Barley	1978	4/01	4/15	8/10
2	Wheat	1979	4/05	4/23	8/15
3	Beans	1973	5/24	6/05	8/28
4	Corn, field	1977	5/05	5/25	9/20
		1980	5/01	5/15	9/29
5	Peas	1977	4/10	4/25	7/25
6	Potatoes	1982	4/25	5/25	10/10
7	Sugar beets	1975	4/15	5/10	10/15
8	Winter wheat	1977-78	10/15	10/25	8/10
		1982-83	10/25	11/10	8/15

[1]Date of beginning of spring growth of established alfalfa.

Alfalfa Reference ET

Daily alfalfa ETR was computed for each of the 7 years listed in Table 7. The 3 years, 1974, 1976, and 1981, were excluded from the 11 year period, 1973 through 1983, because crop growth data were not included for those years. The daily mean ETR calculated for the 7-year period was used to construct an accumulative mean ETR curve for the season as shown in figure 32. The standard deviation of daily ETC is also shown at 10-day intervals, representing the variation within the 10-day period as well as between years. As expected the standard deviation increased during the season.

The cubic equation fitted to the accumulative mean ETR curve of figure 32 was:

$$Y = 313.0 - 10.889 X + 9.77340\text{E-}02 X^{2} - 1.72139\text{E-}04 X^{3}; \quad R^{2} = 0.9999 \qquad [5]$$

where:

Y = estimated accumulative ETR

X = day of year, 90 through 305

The first derivative of Eq. (5), calculated to provide a smoothed daily ETR curve was:

dY/dX

$$dY/dX = - 10.89 + 0.19547 X - 5.16417\text{E-}04 X^{2} \qquad [6]$$

where

dY/dX is equivalent to an estimated daily ETR

Eq. [6] was then used to generate the ETR data for the computation of the individual crop ET values at 5-day intervals throughout the season.

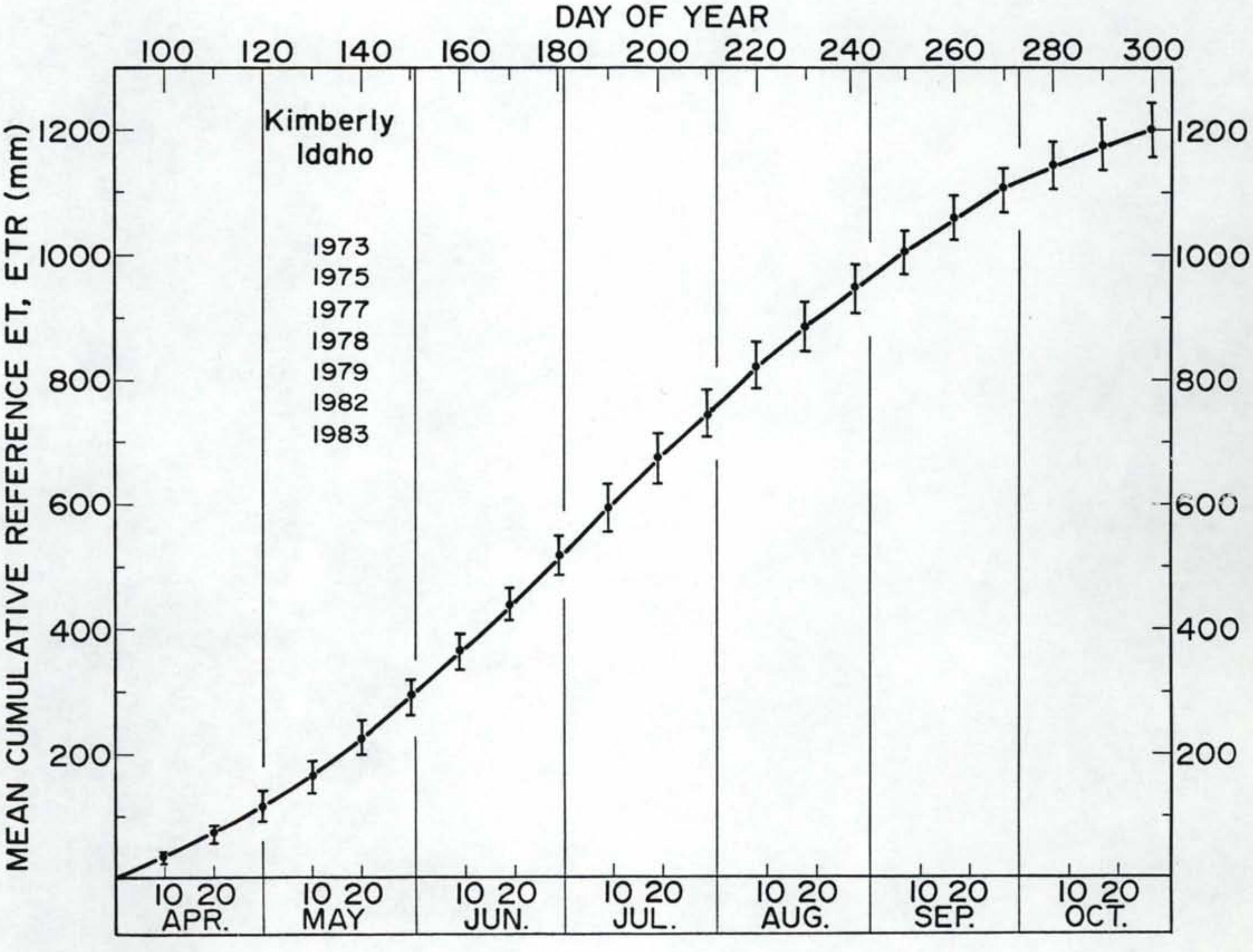

Figure 32. Mean cumulative reference ET (ETR) at 10-day intervals obtained from daily alfalfa ETR data for 7 years of the 1973-83 period with the daily standard deviations from the mean indicated.

Individual Crop ETC, LAI, and DMY

The basic crop-water use and crop growth results are summarized in figures 33 through 40 for the 8 crops of this study, in the same order as listed in table 7. Values of ETC, LAI, and DMY are plotted as smoothed data at 5-day intervals throughout the season, (the DMY data are plotted as 2* DMY for purposes of scale). Results for non-cropped areas are shown in figure 41 and were based on estimates of conditions for such areas. Non-cropped areas include irrigation canals, laterals, ditches, roadways, farmsteads, small towns, etc. The mid-season dip in ETC in figure 41 was based on the supposition that vegetation along roadways and fencelines becomes dormant during late spring after the depletion of available soil water. This condition is eventually offset by growth along water ways and the trees and shrubs surrounding farmsteads or along fencelines so that the net ETC of such areas again increases. The corresponding LAI and DMY data of figure 41 were estimated from results obtained for the other crops.

Comparison of the development of leaf area index and dry matter yield throughout the season as a function of actual crop ET provides a means of considering how remotely-sensed crop material might correspond to crop ET. Visual analysis of figures 33 through 40 indicates that ETC usually approached a maximum level after the LAI reached values of 3 to 4, depending on the crop type, and began decreasing whenever LAI decreased to about the same levels. There is a considerable difference in the general relationship of ETC to LAI and DMY for the various crops because of the differences in growth characteristics. For example, the

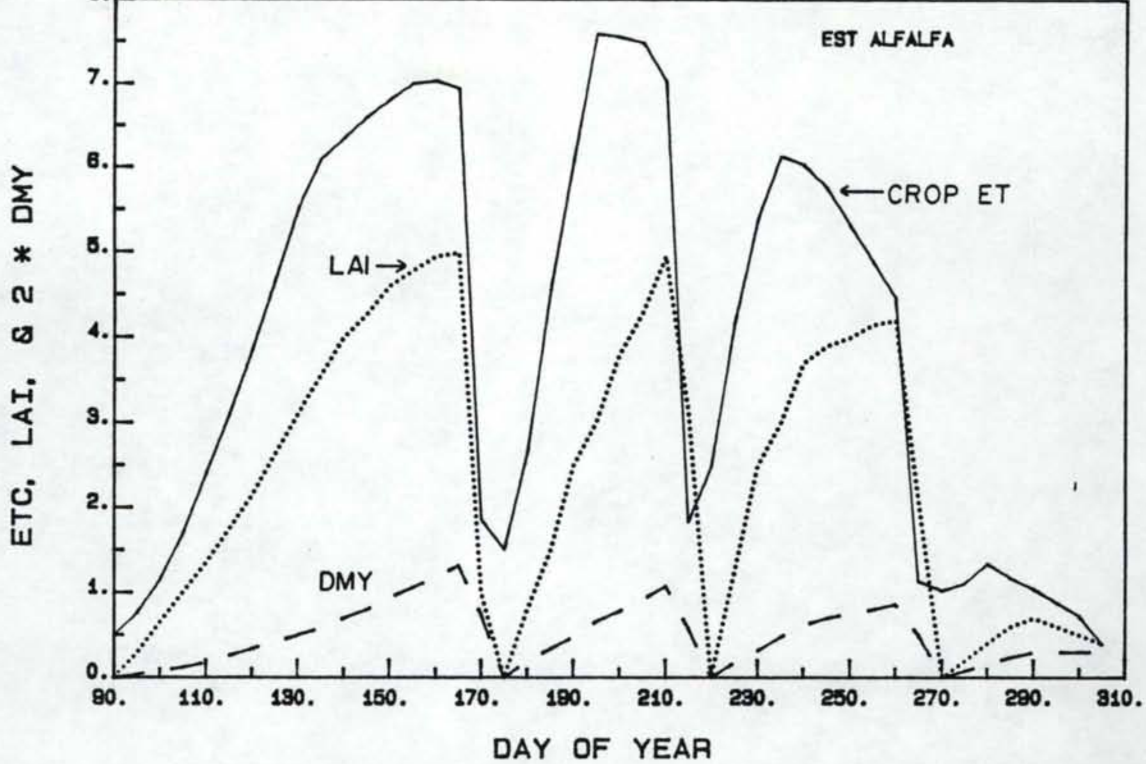

Figure 33. Computed daily crop ET (ETC) in mm/day and smoothed curves of leaf area index (LAI), and twice the above ground dry matter yield (2*DMY) in kg/m^2 for established (est.) alfalfa for the period from 3/31, day 90, through 10/31, day 305.

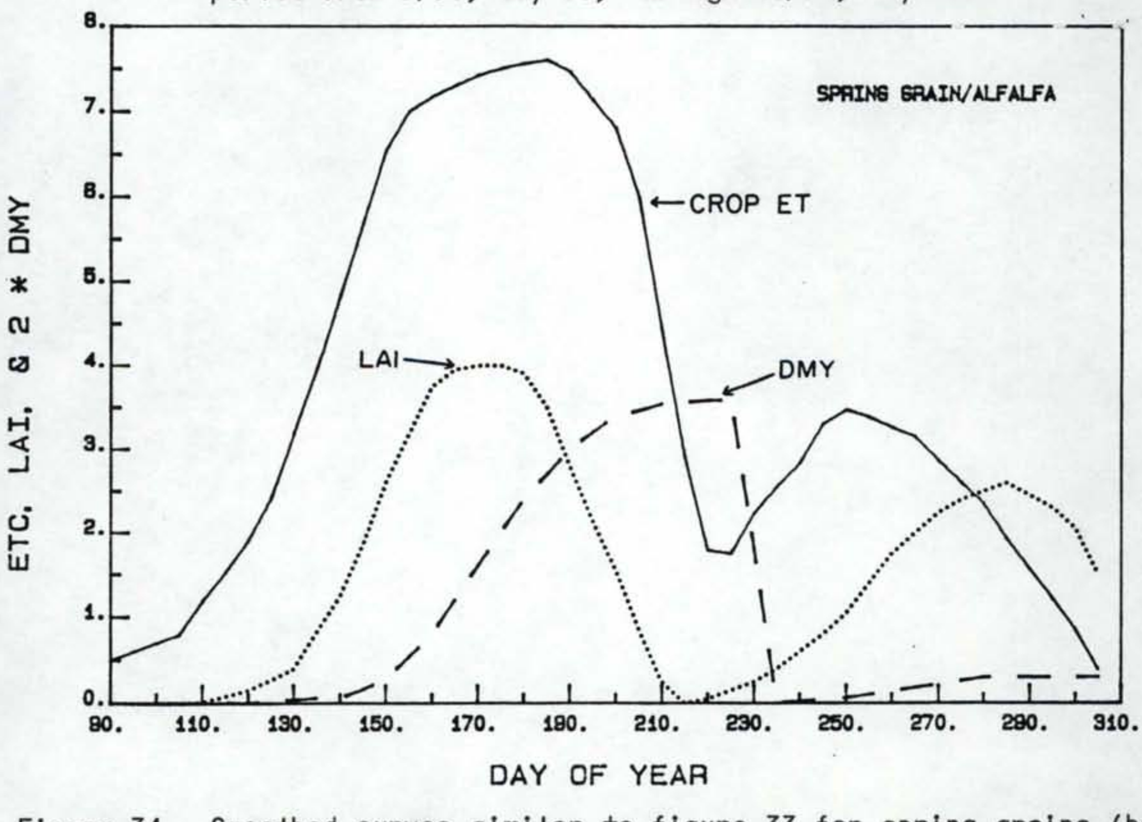

Figure 34. Smoothed curves similar to figure 33 for spring grains (barley and wheat) followed by newly seeded alfalfa.

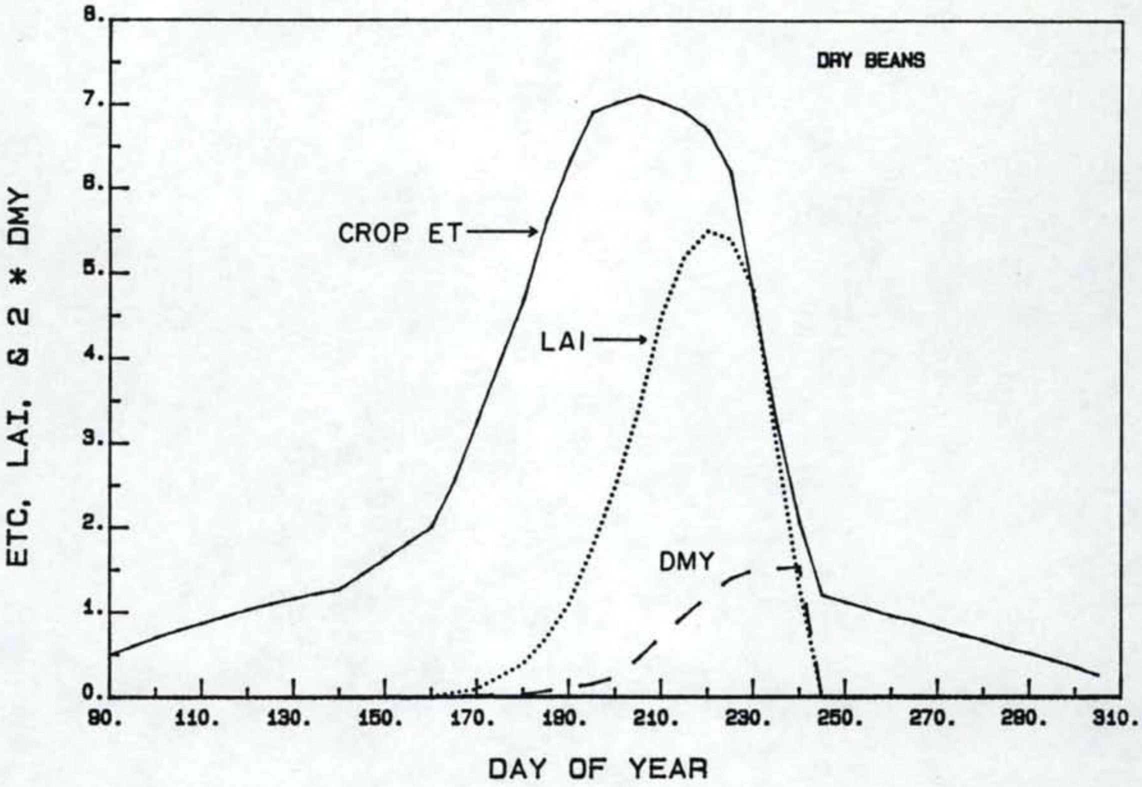

Figure 35. Smoothed curves similar to figure 33 for beans raised for seed (dry beans).

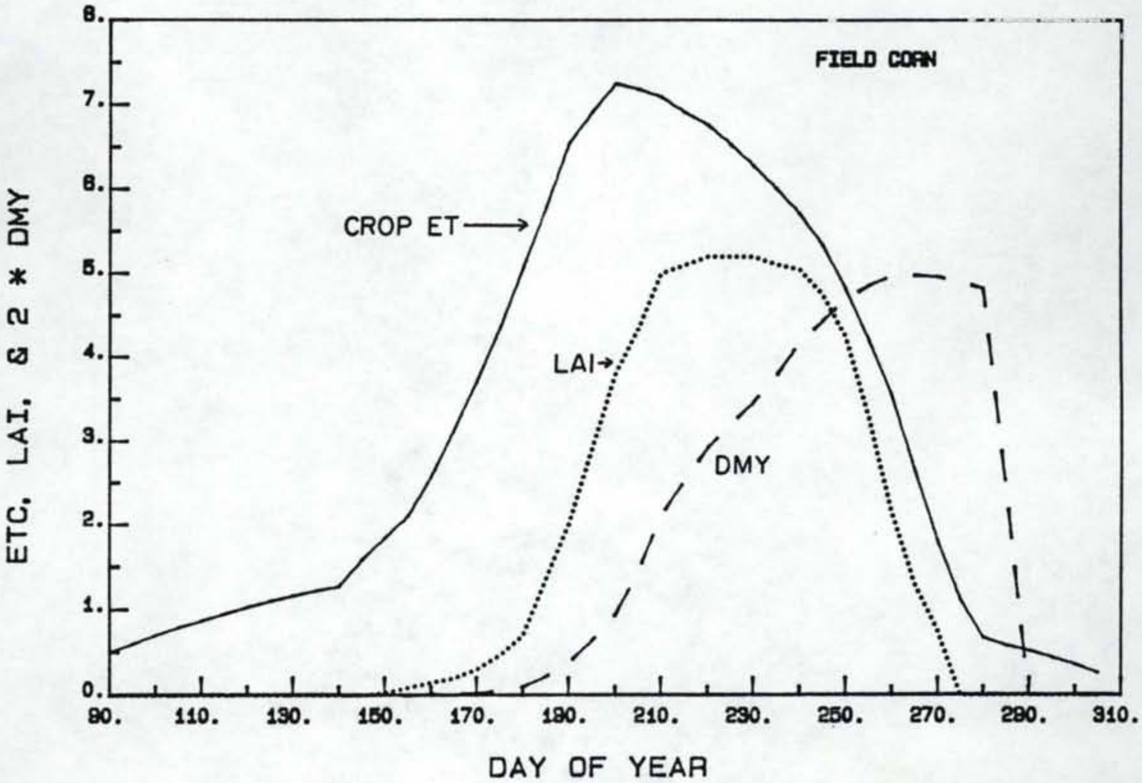

Figure 36. Smoothed curves similar to figure 33 for field corn harvested for silage.

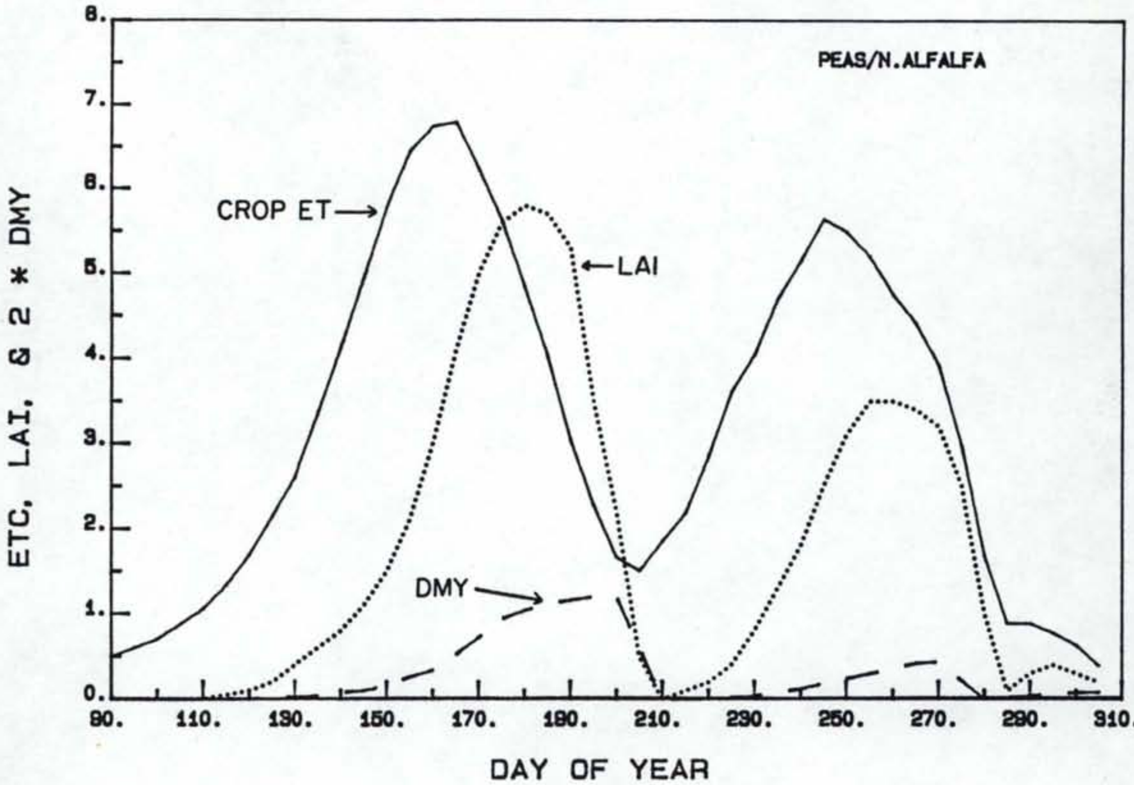

Figure 37. Smoothed curves similar to figure 33 for peas raised for seed and followed by newly seeded alfalfa.

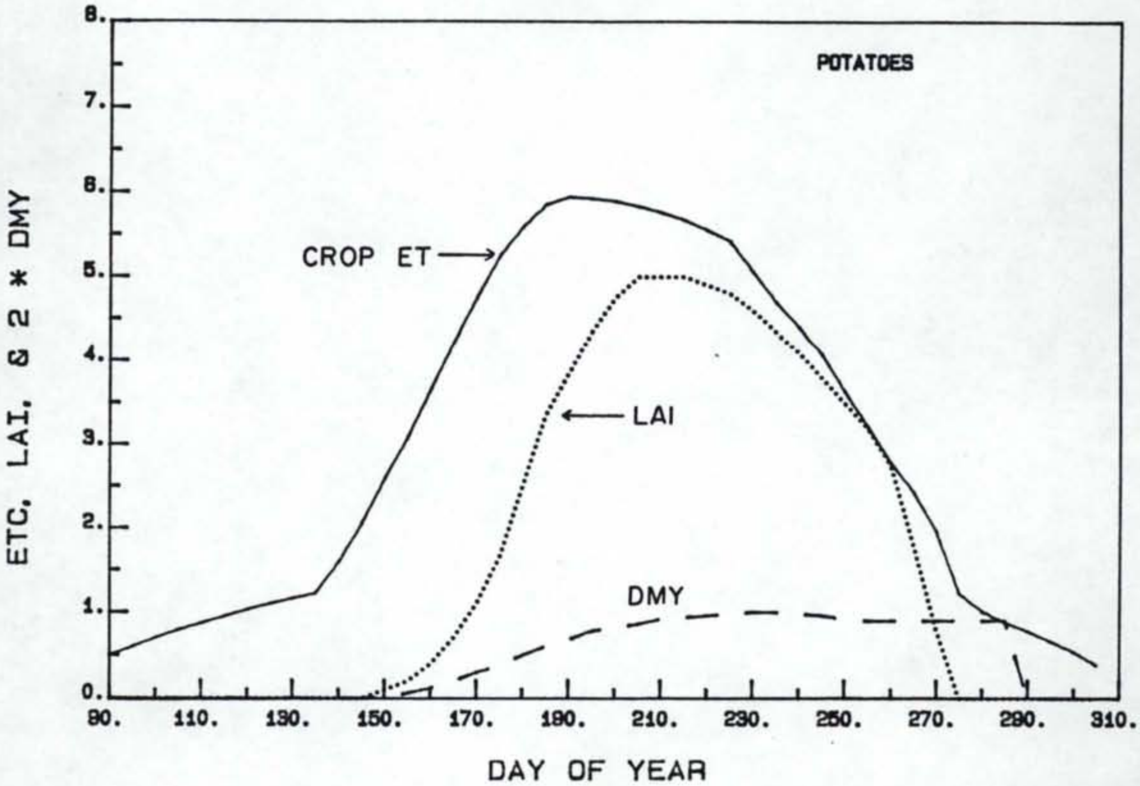

Figure 38. Smoothed curves similar to figure 33 for potatoes (above ground DMY only).

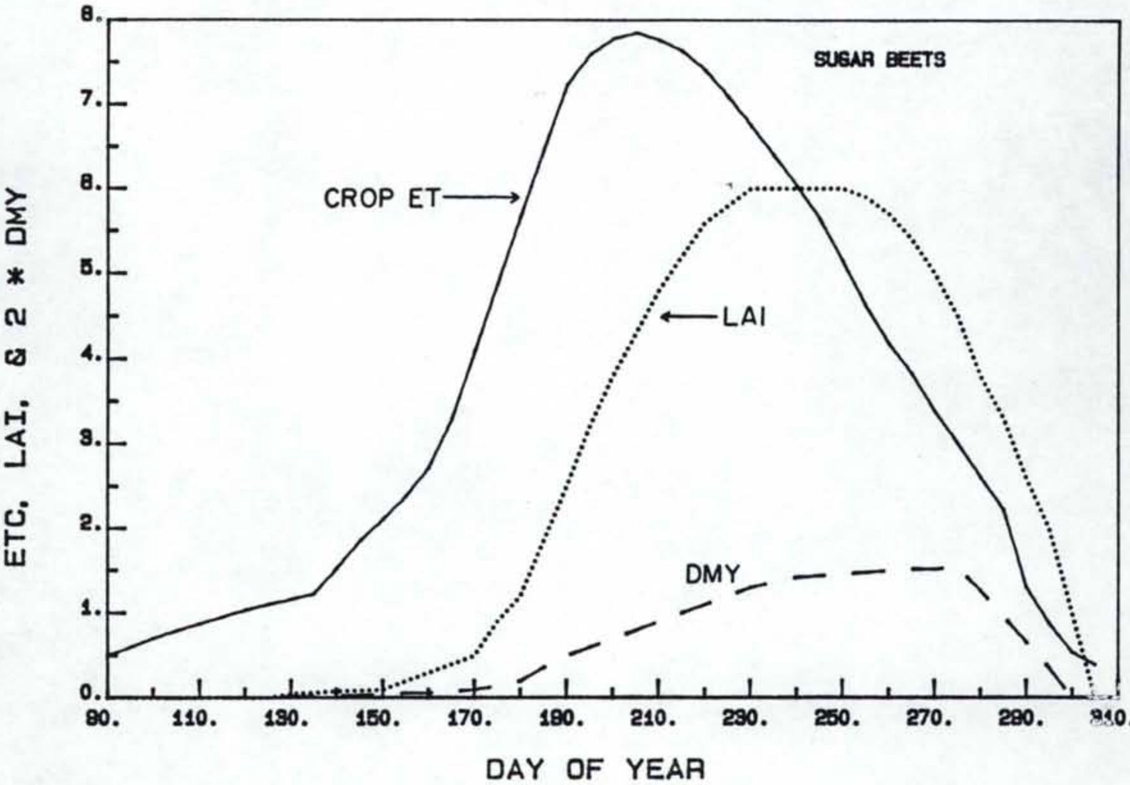

Figure 39. Smoothed curves similar to figure 33 for sugar beets (above ground DMY only).

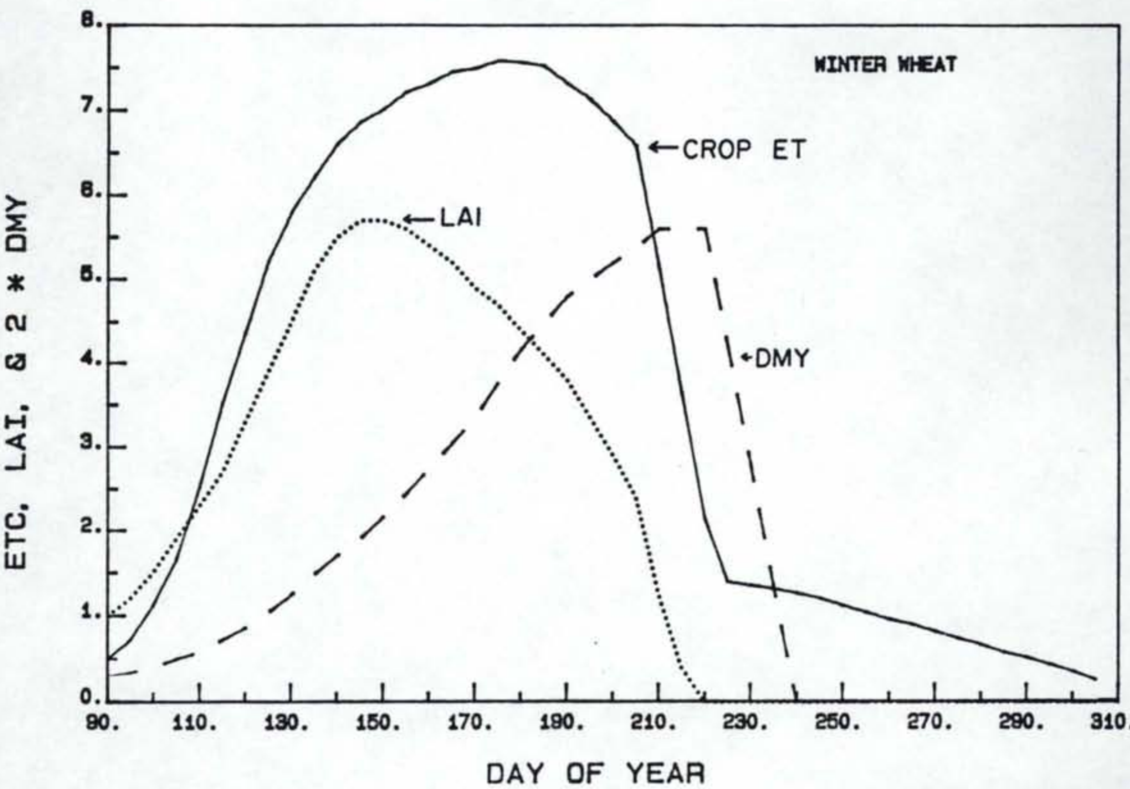

Figure 40. Smoothed curves similar to figure 33 for winter wheat.

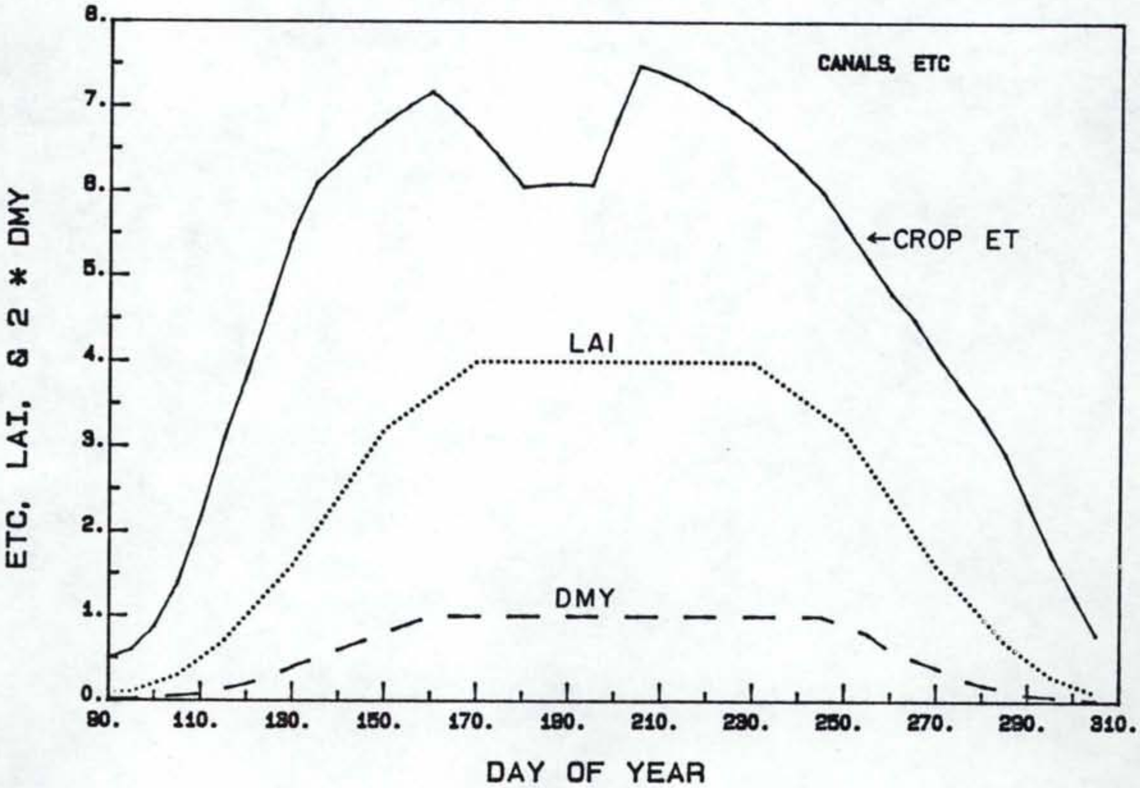

Figure 41. Estimated smoothed curves similar to figure 33 for noncropped areas, such as canals, field ditches, roadways, fence lines, farm steads, small towns, etc.

three curves for established alfalfa show a close correspondence between the three variables; whereas in the case of spring grain, daily ETC continued to increase after LAI reached a maximum and DMY continued to increase even after ETC had begun to decrease. In the case of dry beans, the decrease in LAI closely corresponded to the decrease in ETC and the cessation of increase in DMY corresponded to the decline in LAI. Sugar beets had the highest LAI, while winter wheat and corn had the highest DMY.

The results of figures 33 through 40 do show some common features among the several crops. In all cases, most of the increase in ETC, LAI, and DMY during growth phase 2 was nearly linear with time, indicating that, during this phase, crop growth was closely correlated with the rapid development of leaf area. All of the crops achieved LAI's of at least 4. The increase in LAI was nearly linear with time in the LAI range of 1 to at least 4. The increase in daily ETC was also nearly linear with time in the LAI range of 1 to 3. Daily ETC essentially peaked for most of the crops (all except alfalfa and winter wheat) at an LAI of 4, even though the LAI usually continued to increase to values of 5 or 6 thereafter. Effective full cover was achieved in most cases by the time LAI reached 3. LAI increased from 3 to 4 in only 5 to 10 days. In the cases of beans, corn, peas, potatoes, and sugar beets, daily ETC began to decline from the maximum level after LAI reached 4, even though LAI continued to increase in each case.

The ETC, LAI, and DMY curves were most similar in shape for alfalfa, a forage crop. The crops which have major dry matter accumulation above the ground, in the form of grain or other seeds, such as beans, field corn, and winter and spring grains, show the greatest dissimilarity between the three curves. In these cases, maximum DMY's were reached at about the time ETC dropped to near minimum levels. In fact, a large portion of the increase in DMY occurred for these crops after daily ETC began to decline. In the case of potatoes and sugar beets, the above-ground DMY's reached peak levels fairly early in the growth cycle. Most of the dry matter of these crops is accumulated below ground in the tubers or roots.

The decline in LAI was associated with maturation processes of the crops. This decline usually began before harvest. The rapid decrease in DMY was associated with harvest of the crops.

The seasonal ETC curves of figures 33 through 40 are shown together for all of the eight crops in figure 42 and are grouped into two sections to permit distinguishing the individual curves. Seasonal LAI and DMY curves are similarly shown for each of the crops in figures 43 and 44, respectively. These figures provide a visual composite of the crop response throughout the season. To be particularly noted is the nature of each curve in relation to other curves, the relative rate of increase during the rapid growth phase, the maximum level achieved, and the nature of the curve during the reproductive and maturation phases of growth. The general compensating nature of the combined curves is notable and will be discussed in greater detail in a later section of the report.

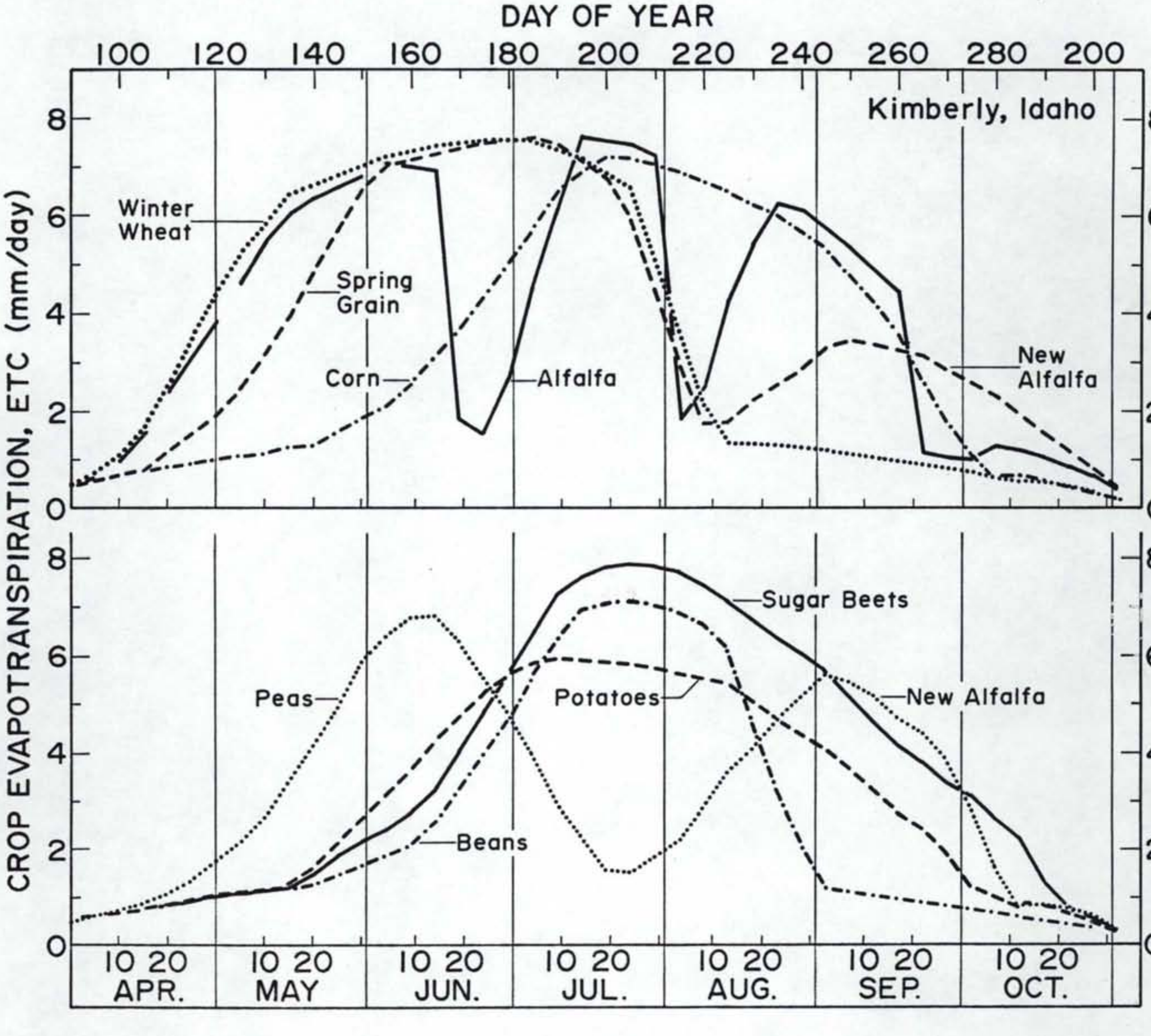

Figure 42. Curves of daily crop ET (ETC) for all eight crops, as shown in figures 33-40, computed from the KCM data of figure 31 and ETR data of figure 31, Kimberly, Idaho.

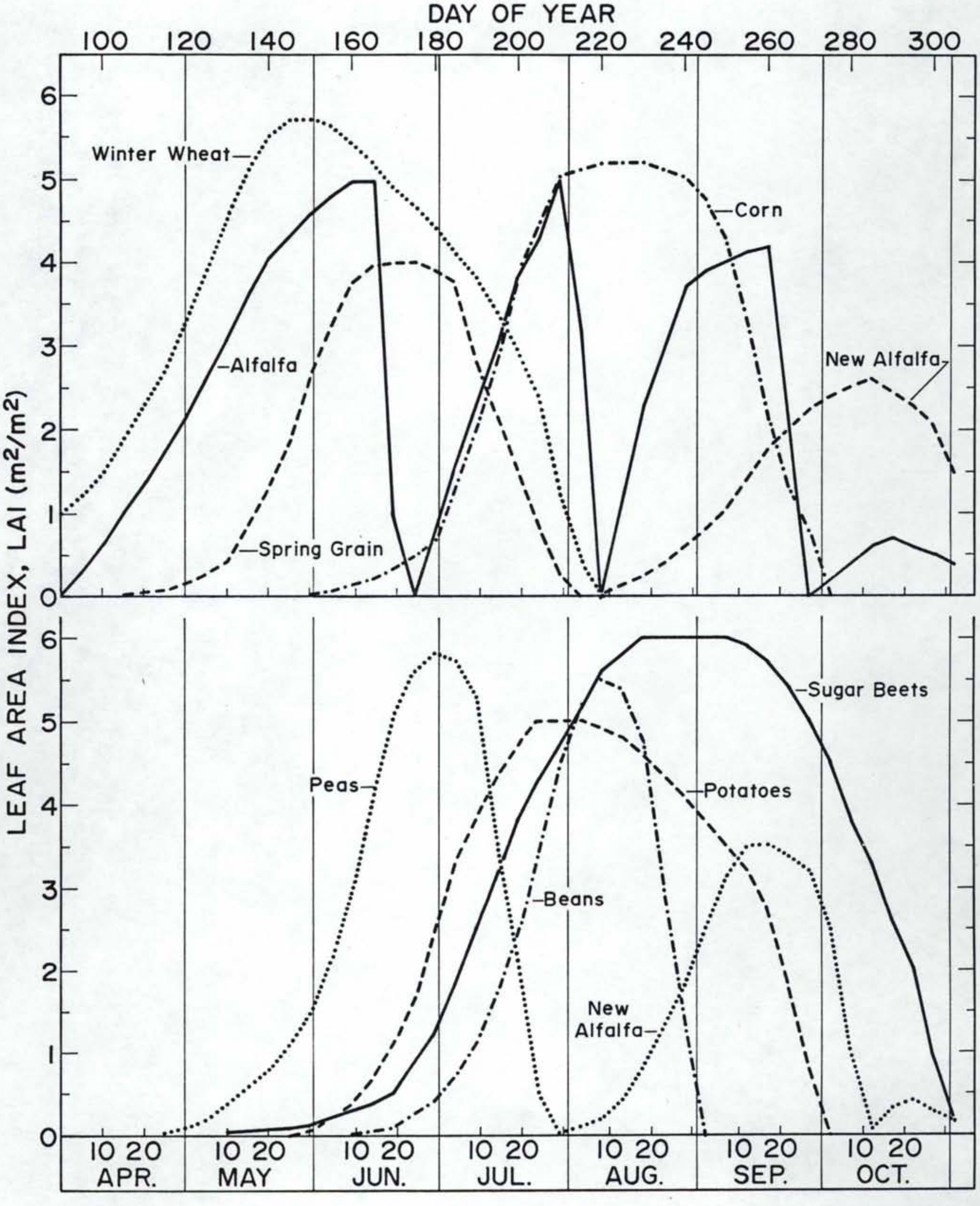

Figure 43. Smoothed curves of leaf area index (LAI) for all eight crops shown in figures 33-40, Kimberly, Idaho.

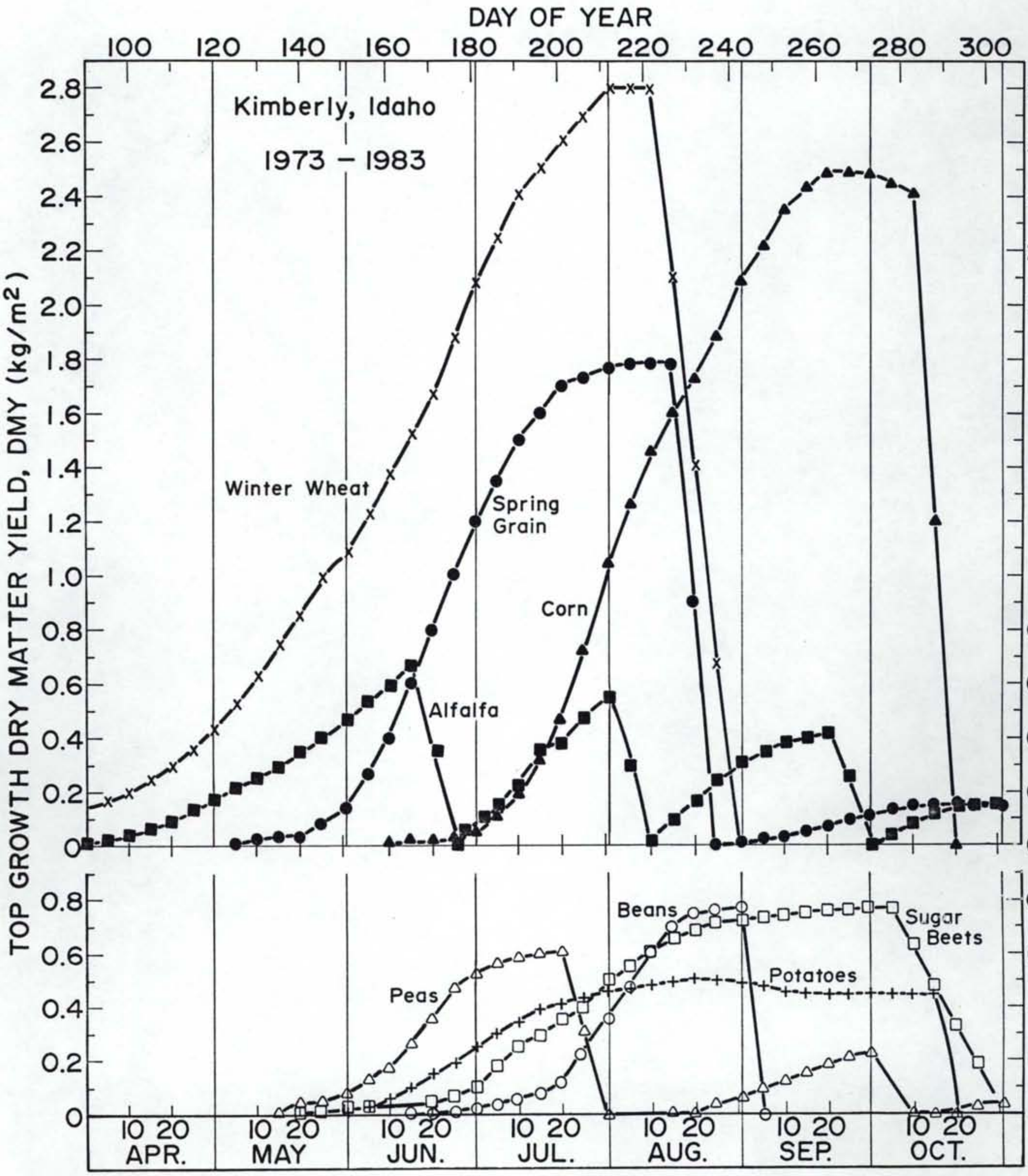

Figure 44. Smoothed curves of dry matter yield (DMY) for all eight crops shown in figures 33-40, Kimberly, Idaho.

Accumulative Growing Degree Days

A growing degree day (GDD) analysis was performed to see if accumulative GDD's during the season corresponded to general crop growth in a manner that would be useful to remote sensing operations. The GDD equation used was:

$$GDD(XX) = (TMAX + TMIN)/2 - TTHR \qquad [8]$$

where the (XX) in the GDD(XX) term is the temperature base, in degrees C, for a particular GDD equation. TMAX and TMIN are daily maximum and minimum air temperatures, respectively, and TTHR is the base temperature all in degrees C. The eight crops were grouped into three categories corresponding to temperature ranges favorable for growth, with lower and upper threshold temperatures respectively, as follows:

Cool	Moderate	Warm
GDD(4.4)	GDD(7.2)	GDD(10.0)
4.4C	7.2C	10.0C
25.8C	27.8C	30.0C
Peas	Alfalfa	Beans
Spring grains	Potatoes	Corn
Winter wheat		Sugar beets

Results for the three crop groups are shown in figures 45, 46, and 47 where the respective accumulative Growing Degree Days are plotted as a function of day of year for the growing period appropriate for each crop. Visual inspection of these results shows that the curves for the cool season crops were quite similar to each other. Likewise the moder ate season curves were nearly coincident. The warm season crops were different but were essentially parallel. Further visual analysis of

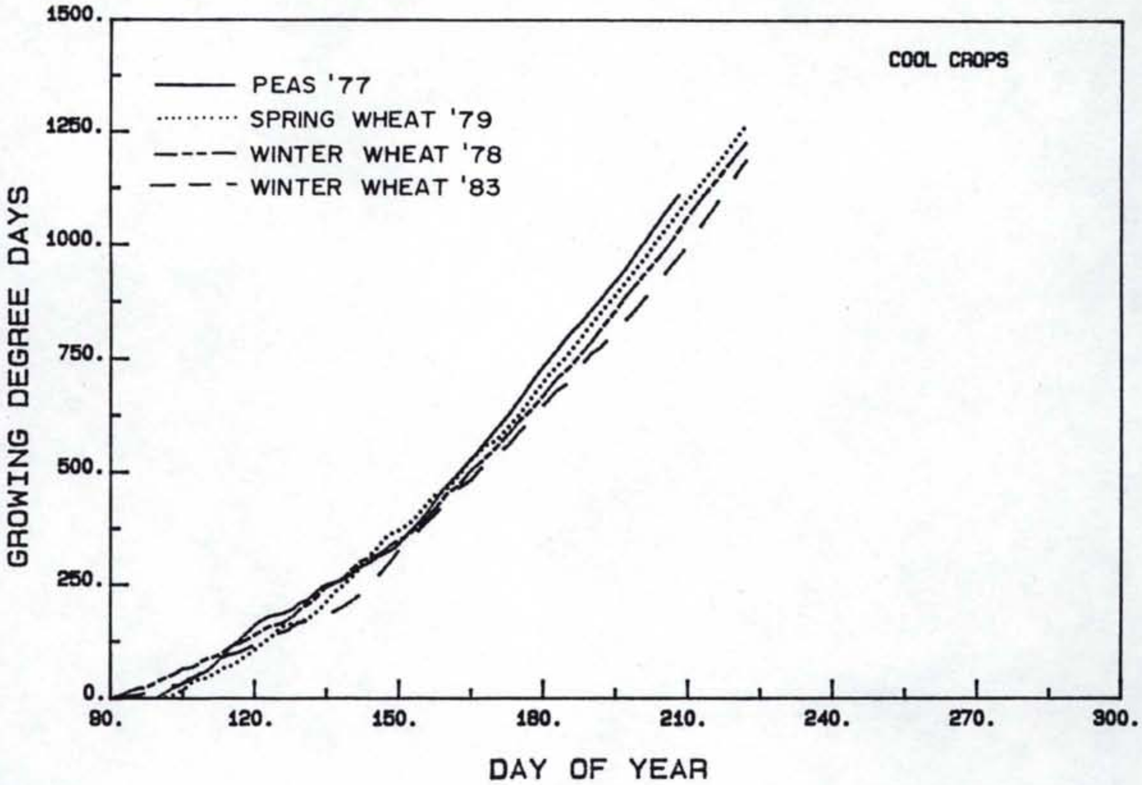

Figure 45. Accumulative growing degree day curves for cool season crops with lower and upper threshhold temperatures of 4.4 C and 25.8 C, respectively.

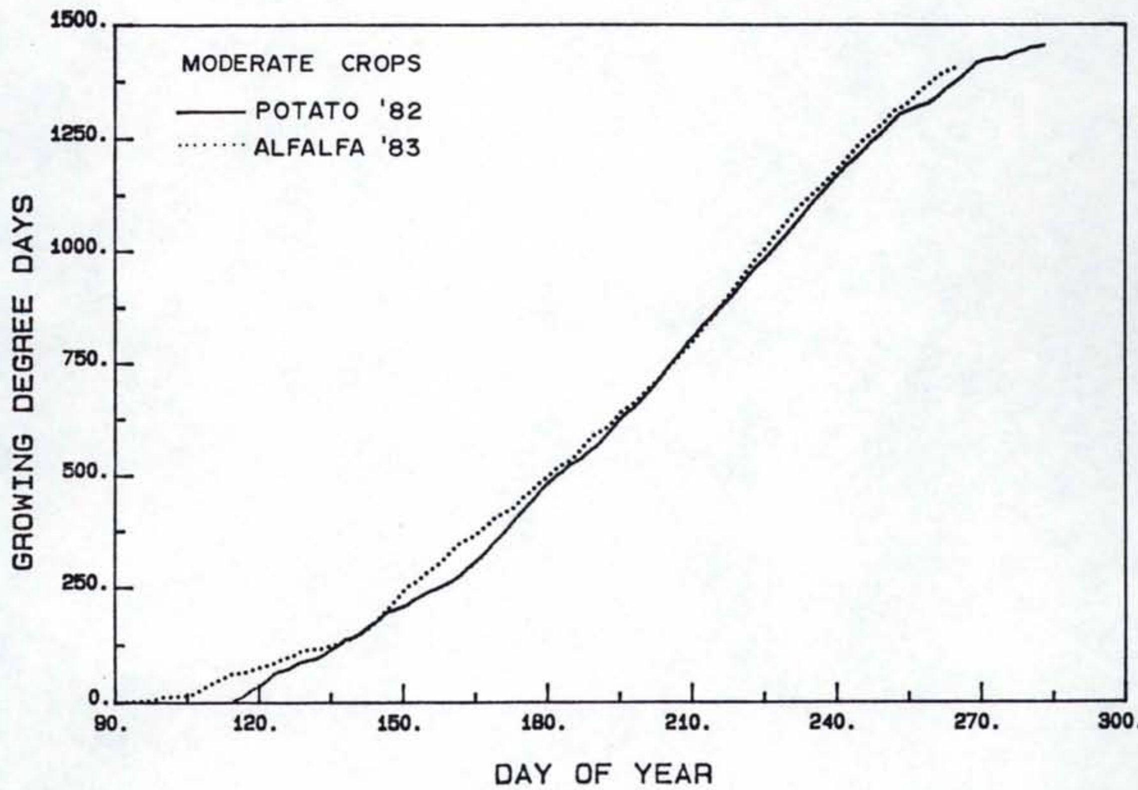

Figure 46. Accumulative growing degree day curves for moderately-warm season crops with lower and upper threshhold temperatures of 7.2 C and 27.8 C, respectively.

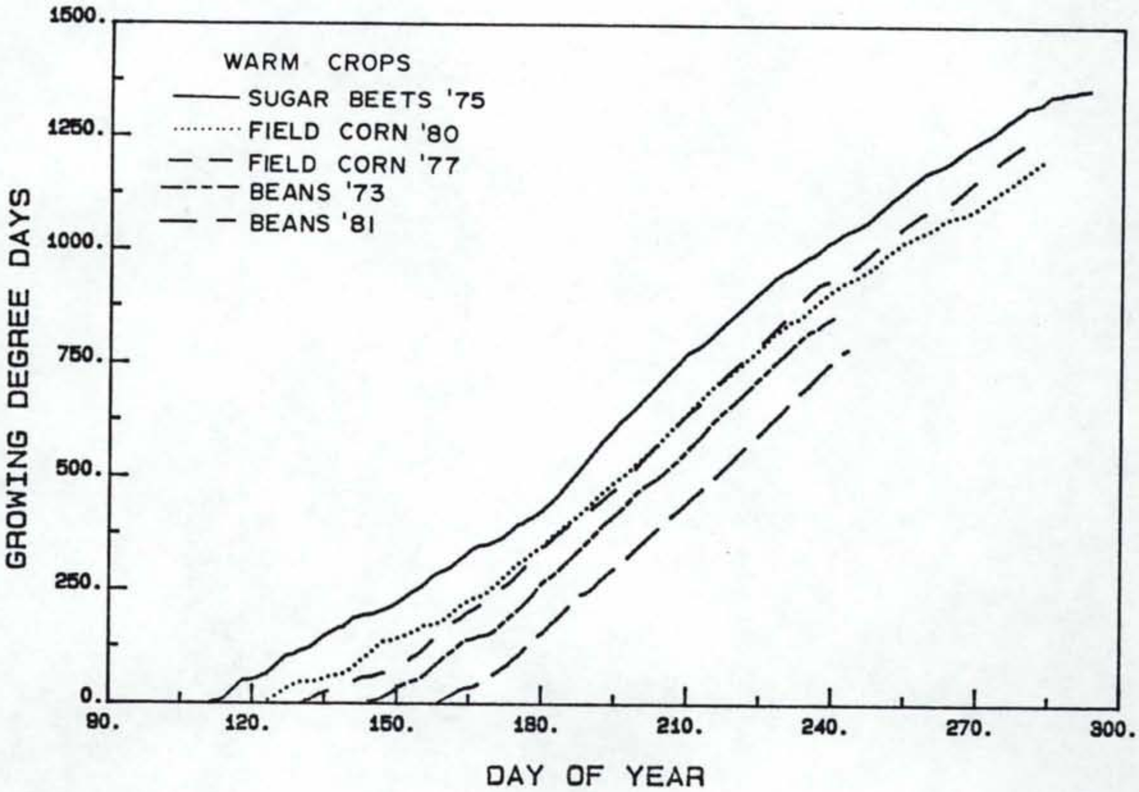

Figure 47. Accumulative growing degree day curves for warm season crops with lower and upper threshhold temperatures of 10.0 C and 30.0 C, respectively.

these results shows that the increase in accumulative GDD's was nearly linear with time during the middle and major portion of the crop period from emergence until a short time before harvest in the case of all the crops. This would lead one to conclude that a growing degree day base is probably not much better than a time base in accounting for differences in the development of leaf area or dry matter as remotely-sensible parameters throughout the season.

There was considerable diversity between the several crops in the relationship of crop ET to the development of leaf area and the accumulation of dry matter. Because of this diversity, it appears that specific functional relationships would need to be developed to characterize each of the crops for remotely sensible properties. Also, since the size of irrigated fields planted to the various crops in southern Idaho ranges from about 2 ha up to 40 ha, there may be some difficulty in accounting for individual crops in developing a regional composite of all crops.

Dry Matter Yield Versus Crop ET

Dry matter yield in kg/m^2 is shown as a function of accumulative crop ET in mm for each of the cereal crops; corn, spring grain and winter wheat, in figure 48; the leguminous crops, peas, beans, and alfalfa, in figure 49; and the below-ground storage crops, potatoes and sugar beets, in figure 50. The crops were grouped into these three cat egories for presentation of results because of the similar nature of the curves in each case. The cereals, of course, developed a fairly strong plant system early, above ground, and then stored considerable dry matter in the form of kernels of grain as well as other plant structures associated with the heads or ears. The leguminous crops also stored considerable dry matter in above-ground structures, but this dry matter is generally higher in protein than that of the cereals. The differ ences in metabolic processes associated with the higher protein synthe sis presumably accounts for the markedly different relationships between cumulative dry matter yield and cumulative crop ET. In general, the

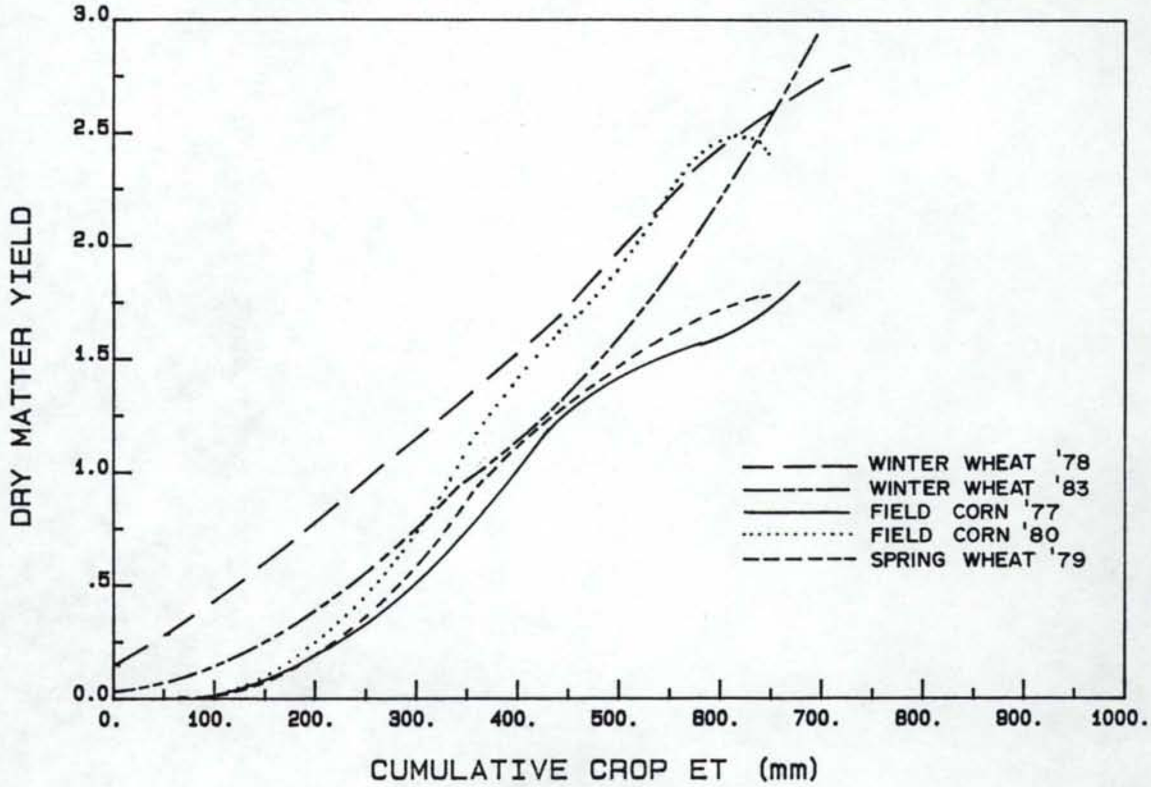

Figure 48. Above ground dry matter yield, in kg/m^2, of cereal crops as a function of cumulative crop ET, Kimberly, Idaho.

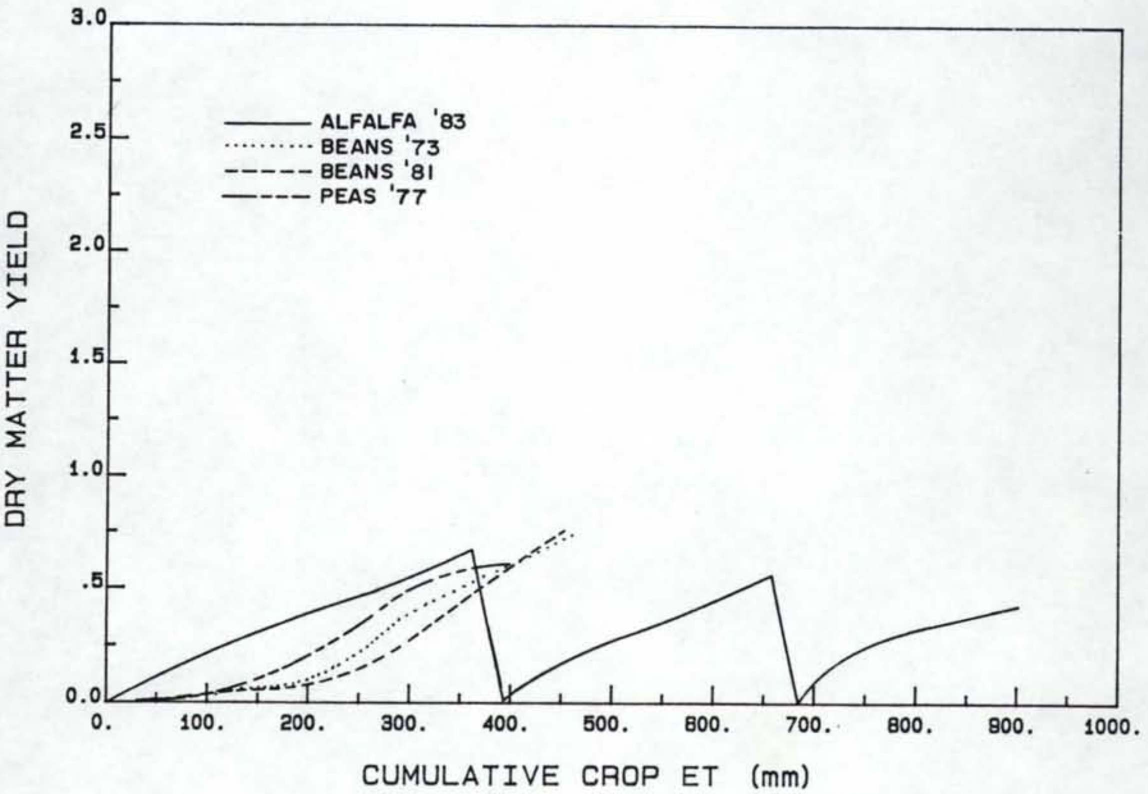

Figure 49. Above ground dry matter yield, in kg/m^2, of leguminous crops as a function of cumulative crop ET, Kimberly, Idaho.

leguminous crops had a higher crop ET per unit of dry matter accumulated than did the cereals.

The third category of crops, those which store dry matter below ground, also have responses different from the others. In these cases, early in the growth cycle, dry matter is invested in developing a large leaf area. Later on, the leaf area is maintained but above ground dry matter remains fairly constant while cumulative ET continues to increase.

The results of figures 48, 49, and 50 do consistently show, as would be expected from inspection of figures 33 through 40, that the accumulation of dry matter is nearly linearly related to cumulative crop ET during the early phases of the crop's growth cycle. During that period plant transpiration is closely related to the development of the above ground plant structures. However, the slopes, general shape, and maximums of the plant growth parameters are somewhat different for each of the individual crops. Furthermore, there is considerable difference from year to year for the individual crops as can be seen by comparing the two curves for winter wheat and the two for field corn with each other. It therefore seems that the ability to sense DMY would only provide an estimate of cumulative crop ET within some rather wide limits.

DMY and LAI versus Crop ET

Of course, remote-sensing devices would generally respond to some combination of crop LAI and DMY, since it probably would not be possible to distinguish between these crop properties. The exact relationship of

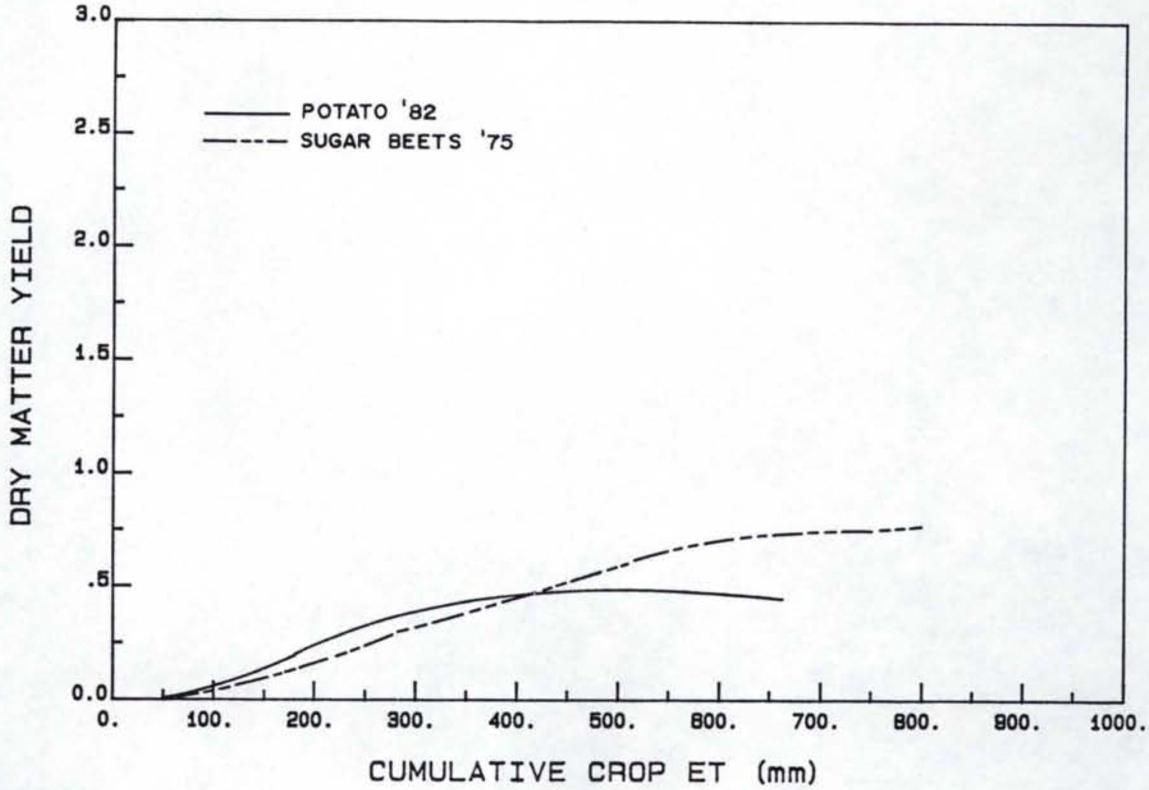

Figure 50. Above ground dry matter yield, in kg/m^2, of root crops as a function of cumulative crop ET, Kimberly, Idaho.

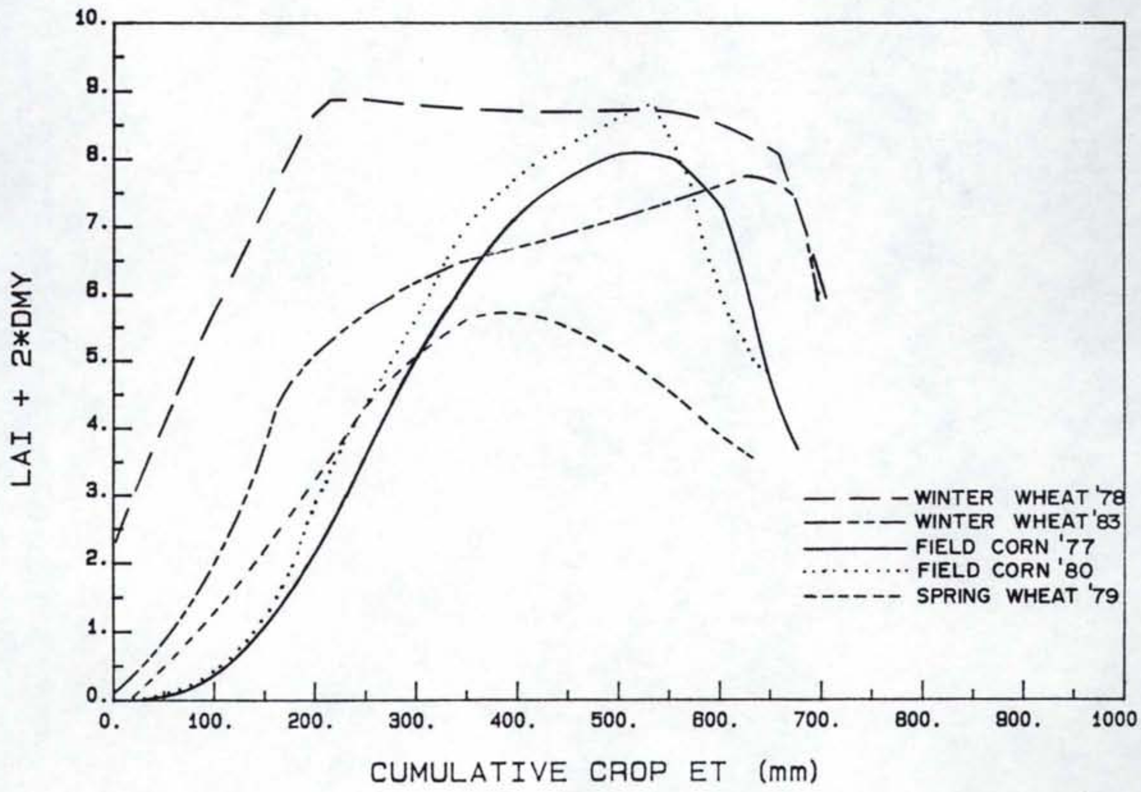

Figure 51. Curves of (LAI+2*DMY) of cereal crops as a function of cumulative crop ET, Kimberly, Idaho.

these two parameters may not yet be known, but it would be expected to be somewhat crop dependent because of the major morphological differ ences between crops. The reflecting or emitting surface area of leaves per unit of dry matter is much greater than that of the surface area of other plant parts, such as stems, leaf petioles, heads, pods, ears, etc.

In an attempt to study the effects of a combination of LAI and DMY, a parameter (LAI + 2*DMY) was used, where DMY had units of kg/m^2, and the factor 2 had inverse units of m^2/kg, producing a unitless product to match LAI. Inspection of figures 33 through 40, for the individual crops, shows that LAI was at least twice that of DMY, when expressed in kg/m^2. For this analysis, it was assumed that the non-leaf portions of the crop plants might be equal in effect to the leaf portions as to radiation/emission properties. Other multipliers than 2, such as 1, 1.5, and 4, were tried but without any marked improvement in the general relationships.

The unitless parameter (LAI + 2*DMY) is shown as a function of accumulative crop ET for the three crop groups in figures 51, 52, and 53 similarly to figures 48, 49, and 50. The shape of these curves is much different than that of those using DMY alone. These results indicate that the relationship of the combination of LAI and DMY to cumulative ETC is much more complex than that of DMY to cumulative ETC alone. However, realistically, the effects of LAI would need to be included in some manner.

The parameter (LAI + 2*DMY) is nearly linearly related to accumula tive crop ET during the first approximately 50% of the growing cycle.

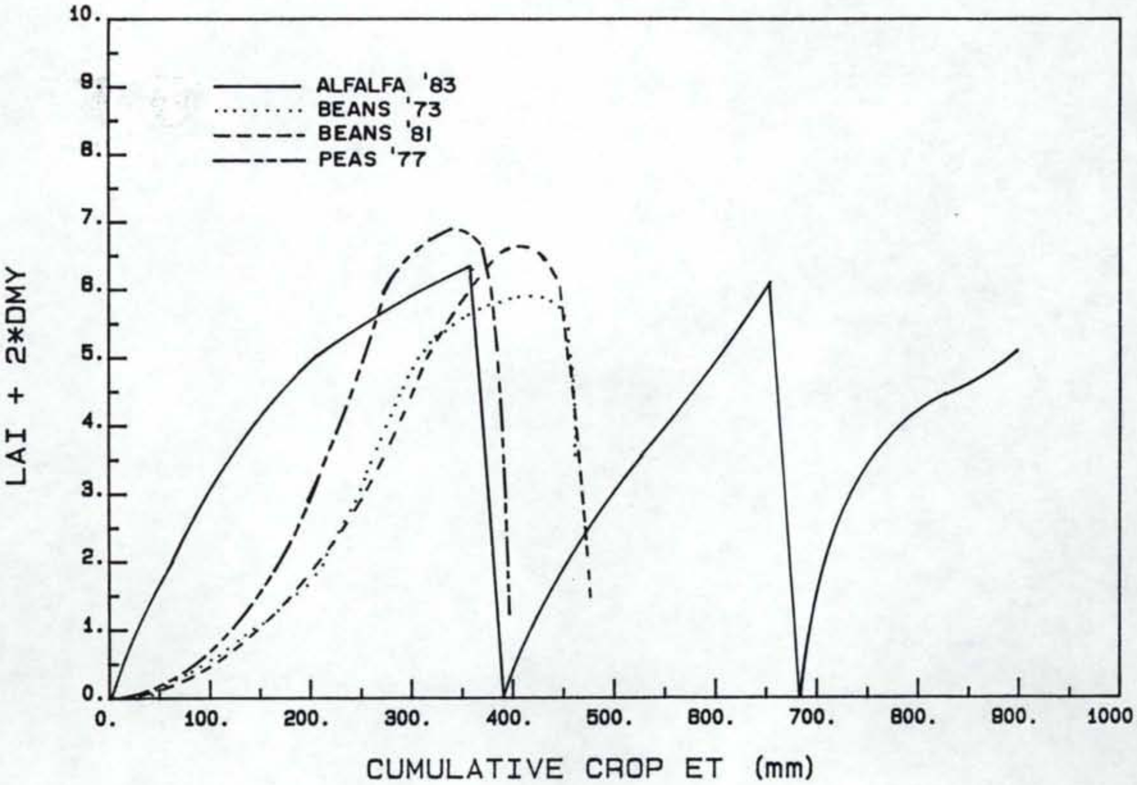

Figure 52. Curves of (LAI+2*DMY) of leguminous crops as a function of cumulative crop ET, Kimberly, Idaho.

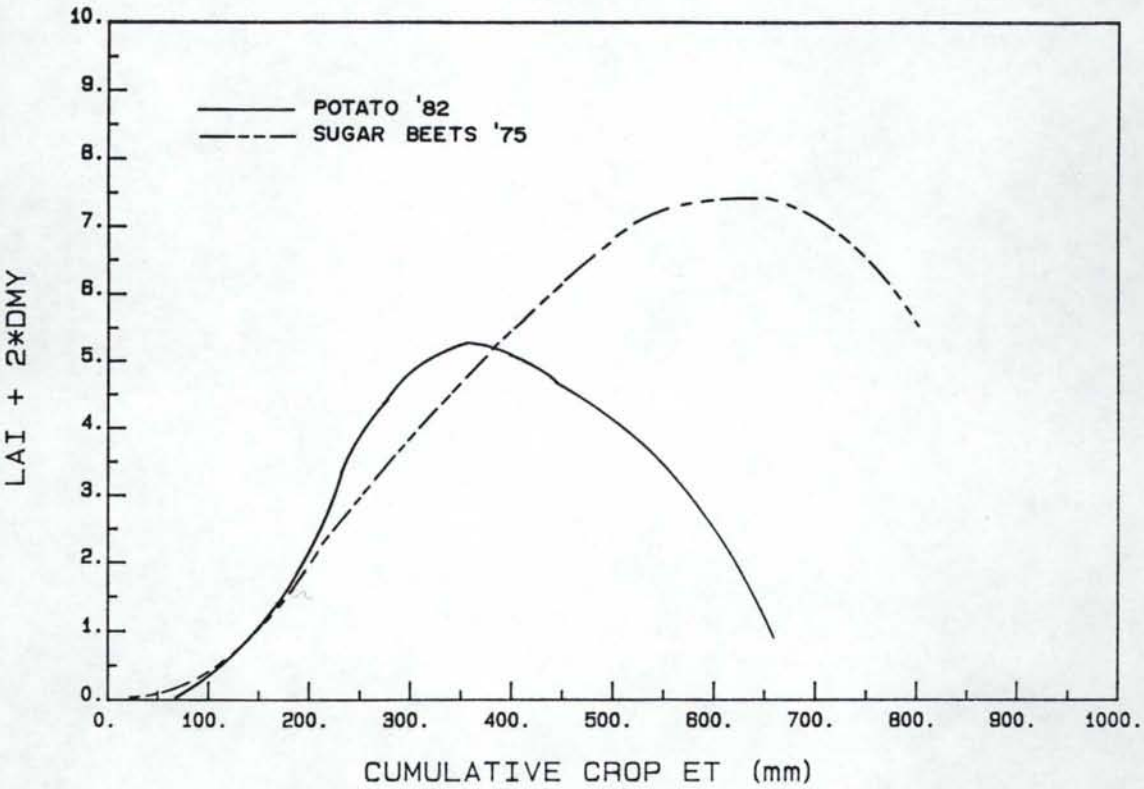

Figure 53. Curves of (LAI+2*DMY) of root crops as a function of cumulative crop ET, Kimberly, Idaho.

After that time, the parameter either becomes nearly constant or eventu ally declines, because of declining leaf area, as the crop matures. However, during this period crop ET continues to accumulate.

While these results indicate that it should be possible to relate the DM of the above-ground portions of the plant to the accumulative crop ET required to produce that amount of crop material, they also show that rather specific functions will be needed to provide reliable relationships.

If it would be possible to relate sensible properties to accumulative ETC, an average of daily ETC could be computed based on the time interval between sensings. For example, if it were found during a particular run, that the (LAI + 2*DMY) was 2 for a crop of corn, which would correspond to an accumulative ET of about 200 mm (see figure 51), and a value of 4, which corresponds to an accumulative ET of 250 mm, was found on a subsequent run 10 days later, then the 50 mm difference over the 10-day period would give a mean daily ETC of 5 mm/day.

Regional Mean ETC, LAI, and DMY

Because of the compensating effects between individual crops in spite of their individual differences, weighted averages of ETC, LAI, and DMY were developed on a regional basis. A mean of all the crops in an area might be directly composited in some remote-sensing processes. Such an approach might be more practical, depending on the scale of sensing, than looking at individual crops on a field-by-field basis.

To accomplish this analysis, the crop mix of the region, developed for earlier portions of this report was used. Table 8 lists the fractional portion of the land attributed to the eight crop groups, as listed in table 7, and a non-cropped area as actually used in this analysis. The sum of the fractional components totals 1.0. The crop mix for other regions will probably differ from that of southern Idaho.

The fractional values listed in table 8 were used to calculate the weighted area average of ETC, LAI, and DMY for the nine crop categories (including the noncropped area) using the basic data for the separate crops, as shown in figures 42, 43, and 44. Results of this analysis are shown in figure 53 where mean daily ETC and ETR are plotted at 5-day intervals along with mean LAI and DMY for the entire 7-month period of April through October. The mean ETR curve is included to show the general nature of reference ET conditions. The mean ETC and mean LAI curves show some remarkable similarities in shape, and the DMY curve follows the same general trend as the other two curves but the variations are less pronounced. The major dips in the ETC and LAI curves at about day 165 were due to the harvest of the first crop of alfalfa. The second alfalfa harvest produced a smaller dip at about day 215. The three parameters, ETC, LAI, and DMY, all peaked between day 200 and day 210.

Table 8. Fraction of irrigated land in region surrounding Twin Falls, Idaho, planted to various crops.

Crop No.	Crop	Fraction of Total Area
1	Est. Alfalfa	0.23
2	Spring grain/ New alfalfa	0.10
3	Beans	0.33
4	Corn	0.06
5	Peans/New alfalfa	0.03
6	Potatoes	0.05
7	Sugar	0.07
8	Winter wheat	0.14
9	Noncropped area	0.19

This similarity of curves, as compared with the diversity between the same parameters on an individual crop basis, indicates that combining the crops produced a blending of individual characteristics with major compensating effects. These results indicate some utility in relating a mean crop ET for a given region to some combination of LAI and DMY, both of which would have direct effects on remotely sensible measurements.

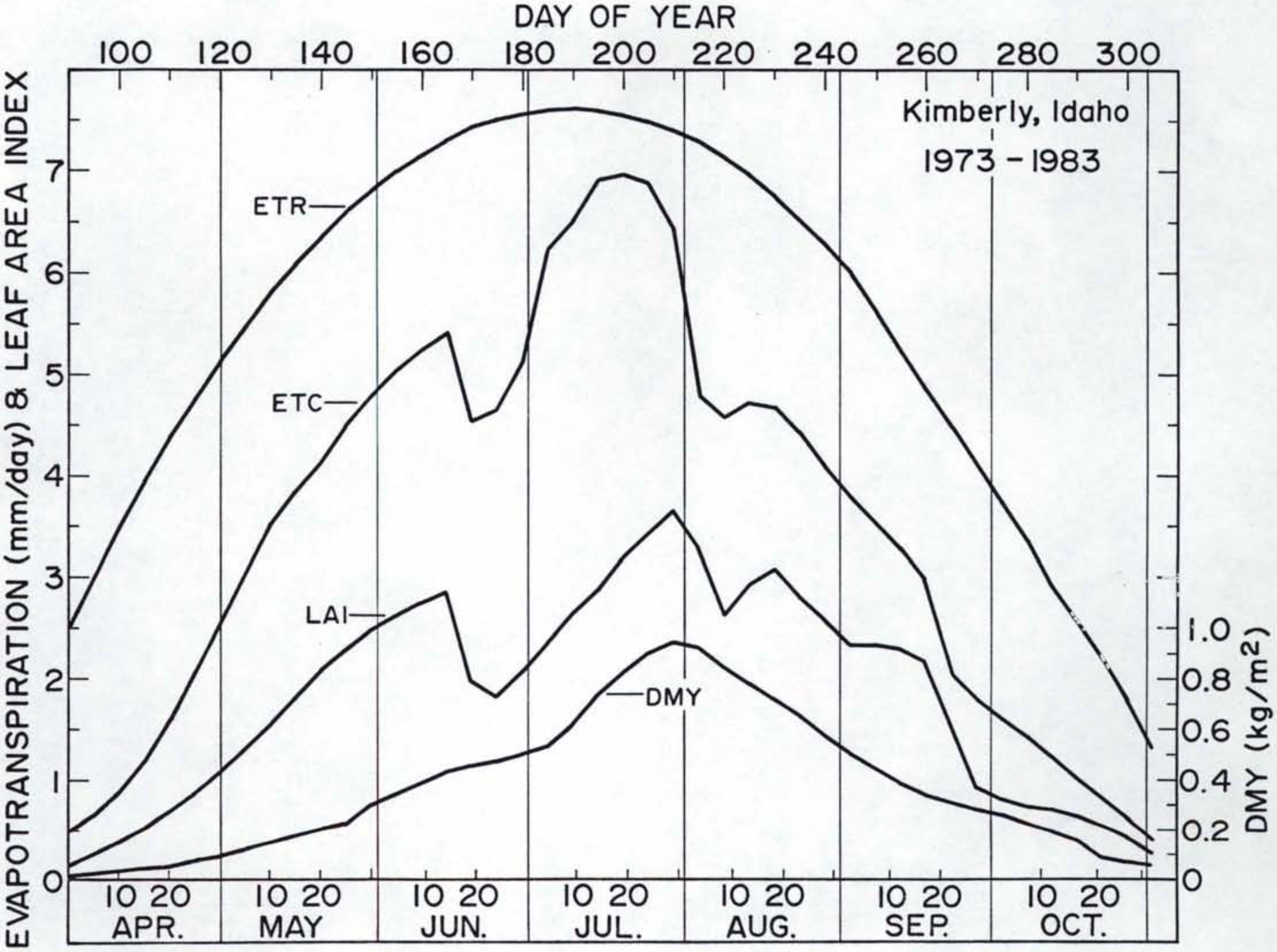

Figure 54. Mean daily reference ET (ETR) and regional, weighted mean curves of ETC, LAI, and DMY throughout the 7-month period.

CONCLUSIONS

Considerable success in the use of remote sensing to detect crop material, or crop biomass, at the earth's surface has been achieved. Concurrently, there has been considerable success in developing techniques for estimating individual crop ET from daily meteorological data and appropriate ET crop coefficients. A logical next step is to merge these capabilities to determine if remote sensing can be used on a real-time basis to directly obtain regional estimates of crop ET or to deliver information that would enhance existing meteorologically based models and facilitate regional ET estimates.

There are limitations in remote sensing techniques to accurate estimation of input parameters for current ET estimating methods. The sensitivity of ET estimates to sensible input parameters may dictate the estimating procedure used or provide relationships to determine confidence limits for estimated ET.

Sensitivity analyses show that errors in measurement of primary input parameters such as temperature, dew point, solar radiation, and wind speed cause significant errors in estimated crop reference ET for all methods using the specific parameters. Errors in temperature measurement, which is a primary input parameter for all methods, result in estimated seasonal ETR errors of 2 to 3 percent per degree F. Consistent error in dew point of one degree F may result in an error in seasonal ET of one percent. Solar radiation sensitivity analysis shows that a consistant overestimation of 80 langleys/day could result in overestimates of 8 to 10% in seasonal ETR. Sensitivity of monthly ETR to input parameters depends on base conditions for a particular month. This analysis provides guidelines to allow determination of applicability of specific remote sensing procedure or sensor procedure accuracy.

Utilization of group crop coefficients to accomodate the lack of sensor discrimination for specific crop type is feasible. The larger the number of crops in a group, the larger the potential error in actual ET estimates. If the actual crop distribution for the pixel contains an equal percentage of all crops represented by the group crop coefficient, then no error is introduced in the ET estimate. Maximum error in estimated ET will occur when the group crop coefficient is used and the actual crop distribution includes only the crop with the maximum or minimum crop coefficient for the group for the month or season. This condition is not likely to occur and historical crop distributions could be used to reduce the potential error.

Grouping error is most pronounced during mid-season when reference ET is near maximum. Maximum seasonal error is not equal to the sum of daily errors since the maximum and minimum ET for any day may be due to different crops. For instance, if an area is represented by a row crop group crop coefficient and in reality the only crop growing is sugar beets, maximum daily errors in ET will occur during late summer when sugar beets have the greatest transpiration rate. If sensor discriminiation will allow crop grouping of either single crops or groups such as small grains or alfalfa and grass, then maximum possible errors due to grouping of 4 to 13% in seasonal ET may be achieved. However, if only broader groups containing, for instance, all row crops, then maximum possible errors of 13 to 35% may occur. Probable errors considerably lower are likely since actual crop distributions are unlikely to contain only a single crop. Development of group crop coefficients and compatibility with sensor type to determine probable errors due to grouping and recognition error should be evaluated and field verfied.

Data presented in this report definitely show that there are definable relationships between daily crop ET and the extent of crop growth as measured by leaf area index and/or above ground dry matter. These relationships are best defined during the rapid growth phases of crop development. They become quite complex during the reproductive and maturation phases of growth. The development of leaf area and above ground dry matter is nearly linearly related to daily crop ET until the time of effective full crop cover when ET approaches maximum levels. For given crops and years, the accumulation of dry matter is also nearly linearly related to accumulative crop ET over a large portion of the growing season. However, the relationships differ for different crops and from year to year for the same crop.

The results show some promise in adapting remote sensing capability to the estimation of regional ET. However, the results also indicate that the individual crops need to be characterized as to remotely sensible properties and the relationship of these to ET. The variation evidenced indicates that there realistically may be rather wide limits to the accuracy of estimating crop ET from measurements related to crop biomass.

Before further progress can be made on the subject of individual crop behavior, more definite information is needed on the exact capability of remote sensing techniques to identify crop types on a field-by-field basis. More information is needed on the capability of remote sensing to quantify the biomass present and the varying response throughout the season for each of the growth phases of a crop. The effects of crop leaf area and accumulated dry matter are specifically needed.

The results of a composite crop group response to daily crop ET tentatively appear more straightforward than working with individual crops and then developing regional averages. A composite crop response would include a large enough area to be representative of the major crops grown. However, while the approach shows promise, more specific information and field verification is needed to determine what physiological parameters a remotely sensible crop composite might represent.

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APPENDIX A

Monthly Sensitivity of ET Estimates

to Input Parameters

Kimberly, Idaho

Figures 1-7 are plots of monthly sensitivity of ET to temperature from April through October. Figures 8-14 show monthly sensitivity to dewpoint; figures 15-21 show monthly sensitivity to solar radiation; and figures 22-29 show monthly wind sensitivity.

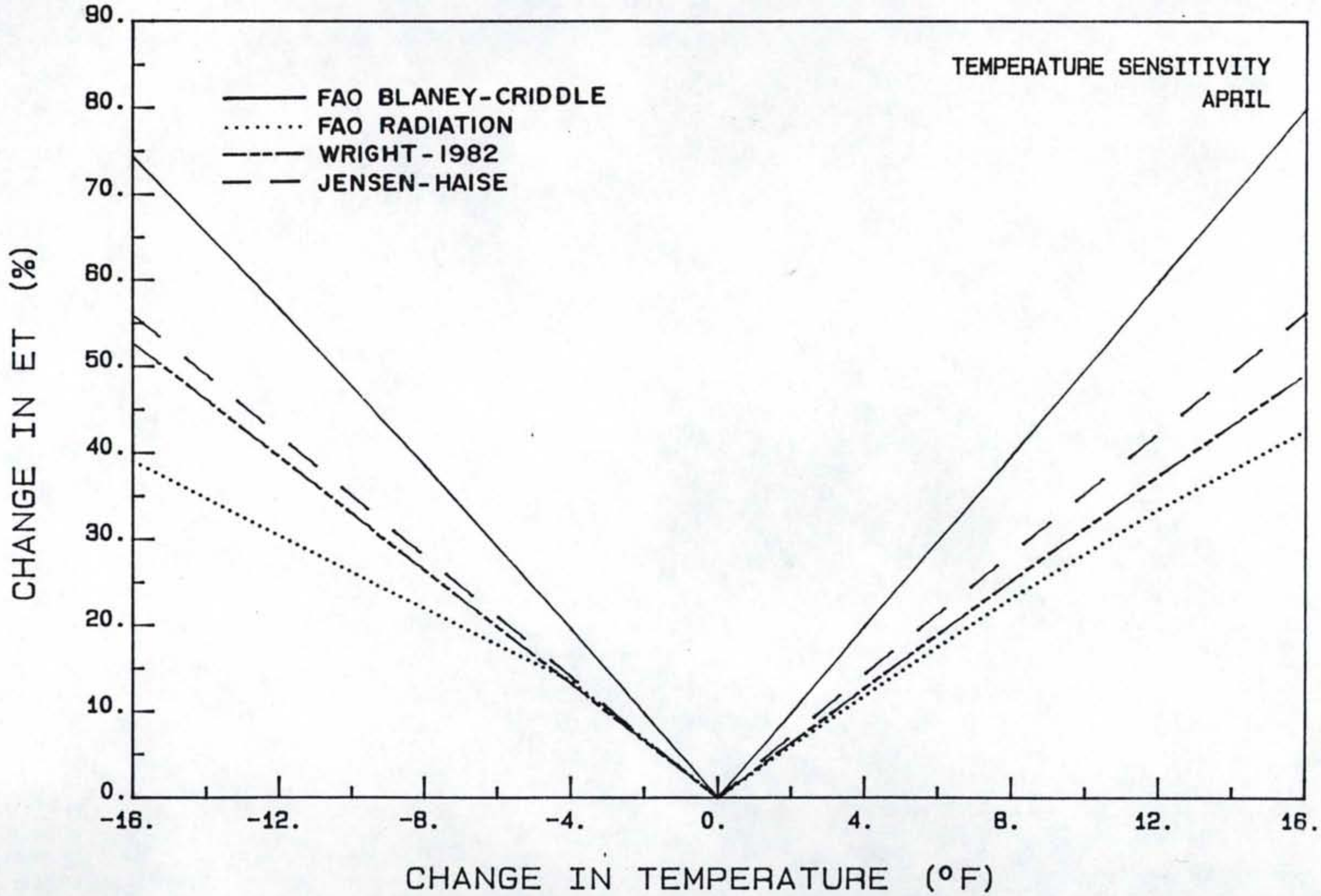

Figure A-1. Temperature sensitivity for April, Kimberly, Idaho.

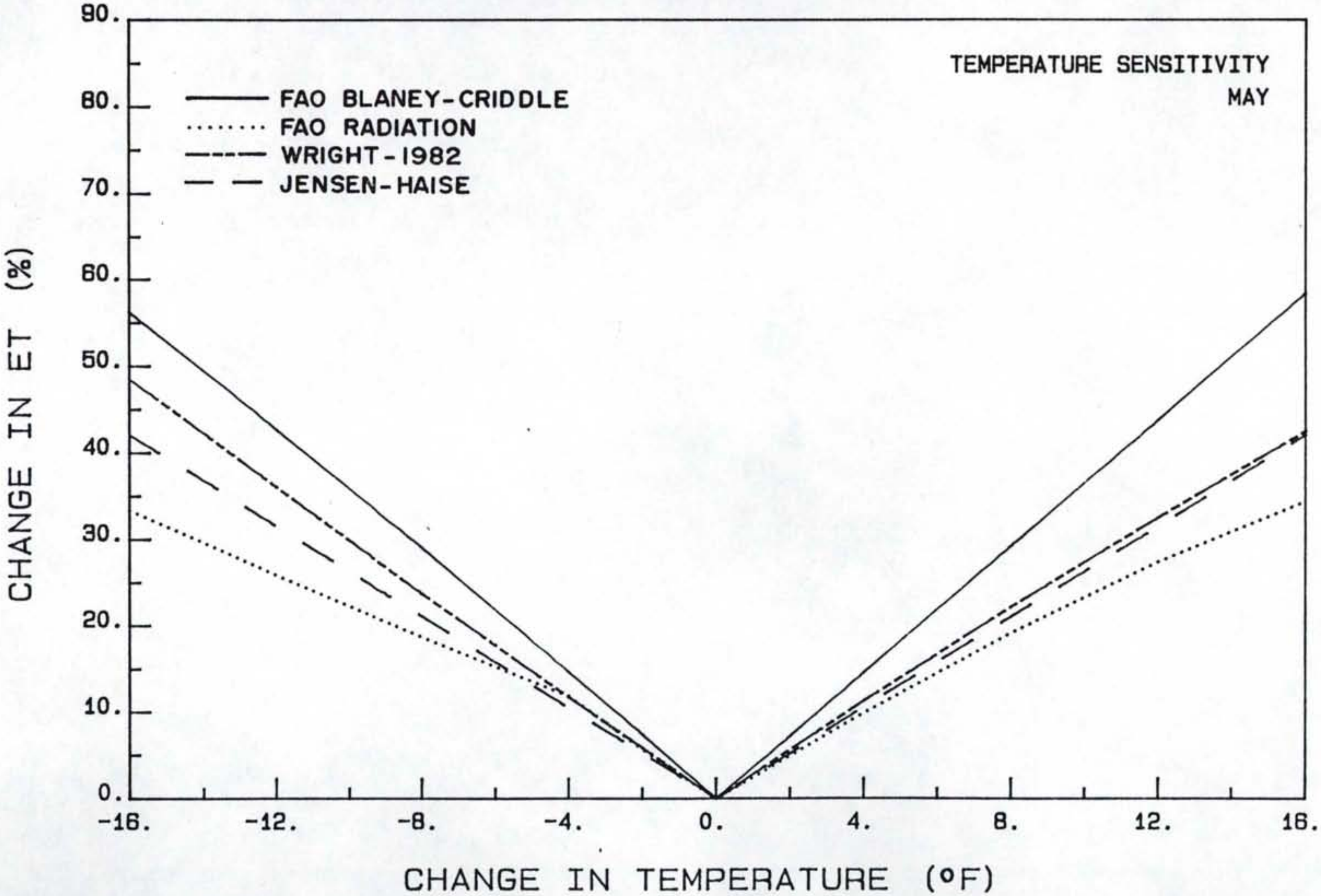

Figure A-2. Temperature sensitivity for May, Kimberly, Idaho.

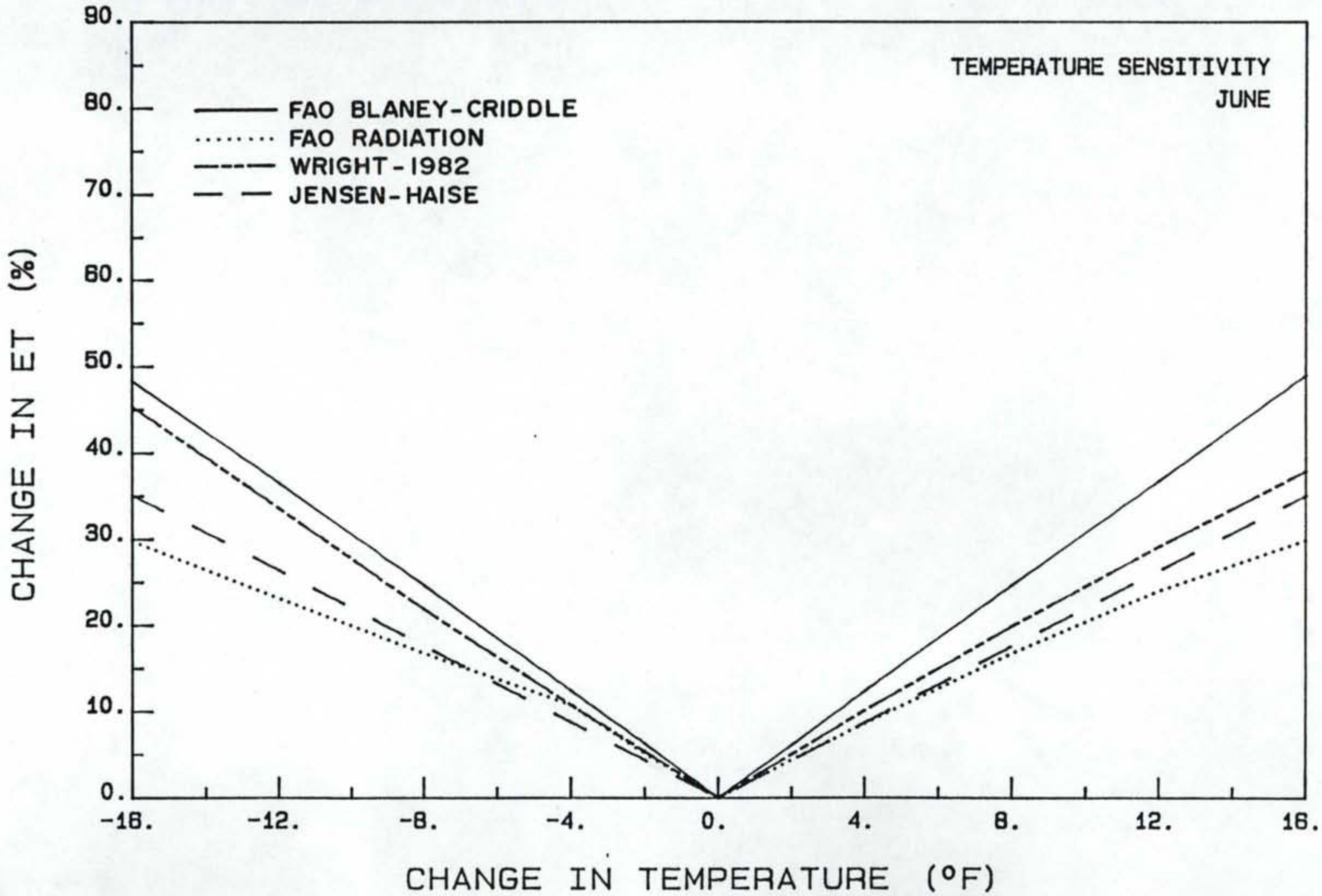

Figure A-3. Temperature sensitivity for June, Kimberly, Idaho.

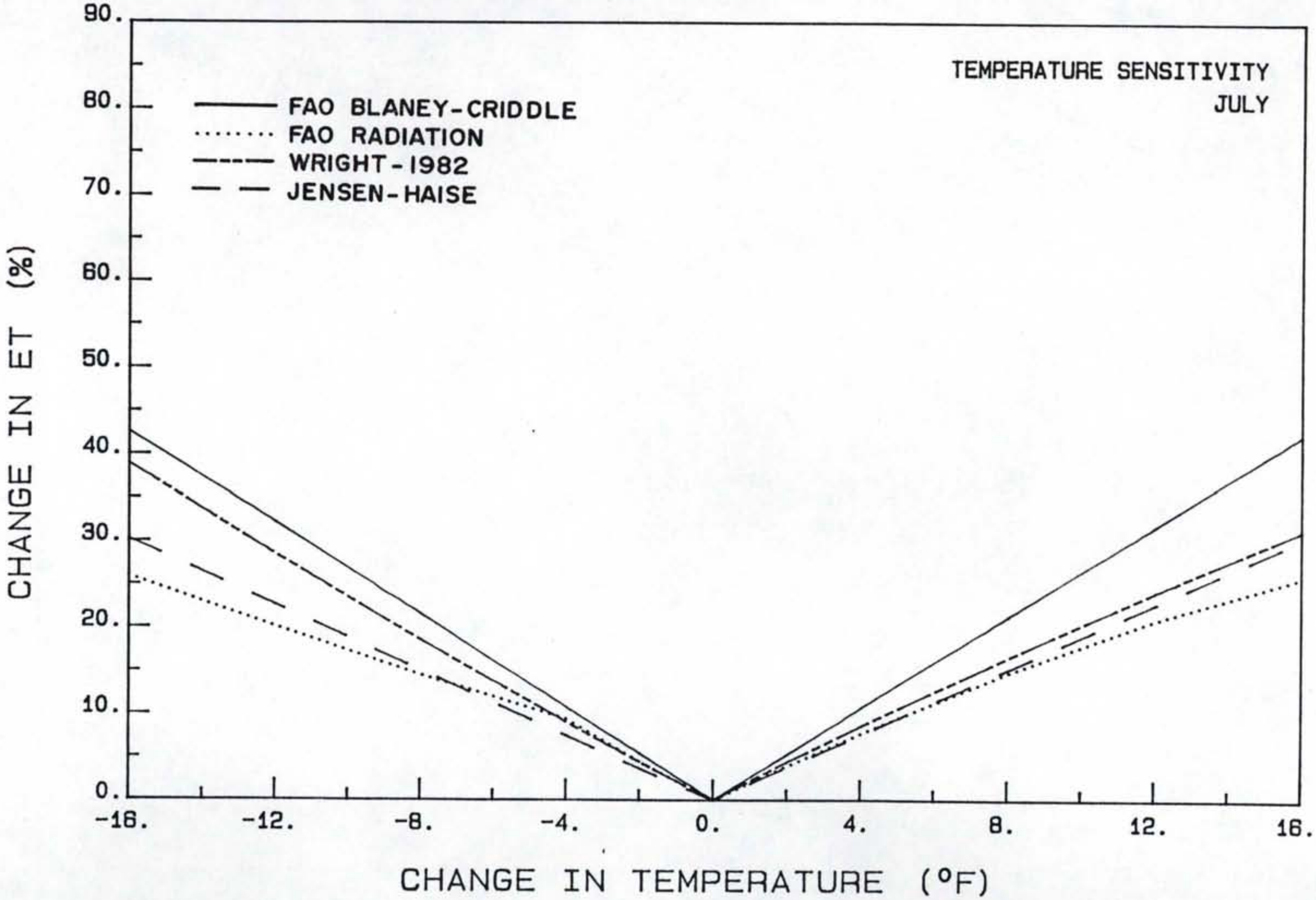

Figure A-4. Temperature sensitivity for July, Kimberly, Idaho.

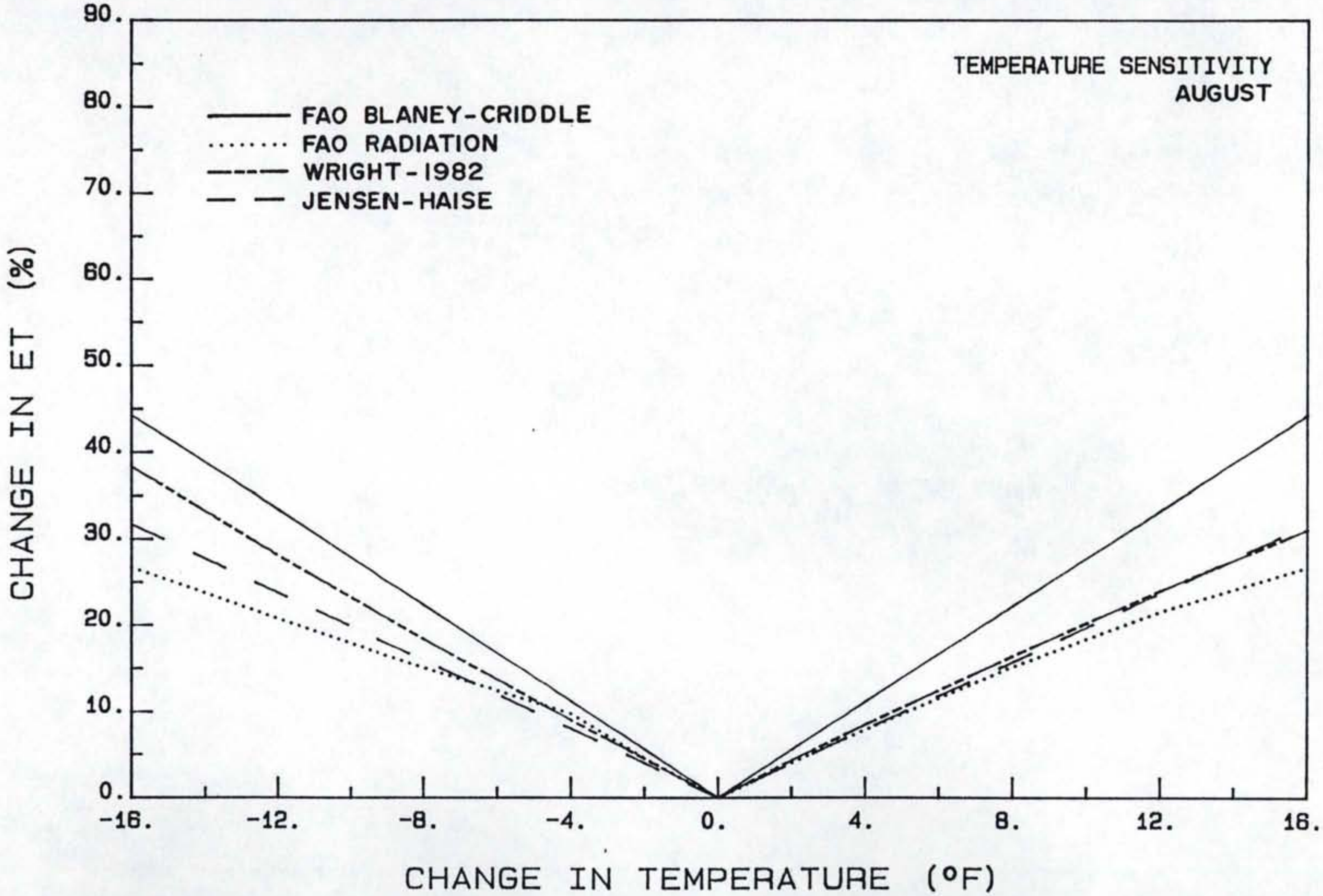

Figure A-5. Temperature sensitivity for August, Kimberly, Idaho.

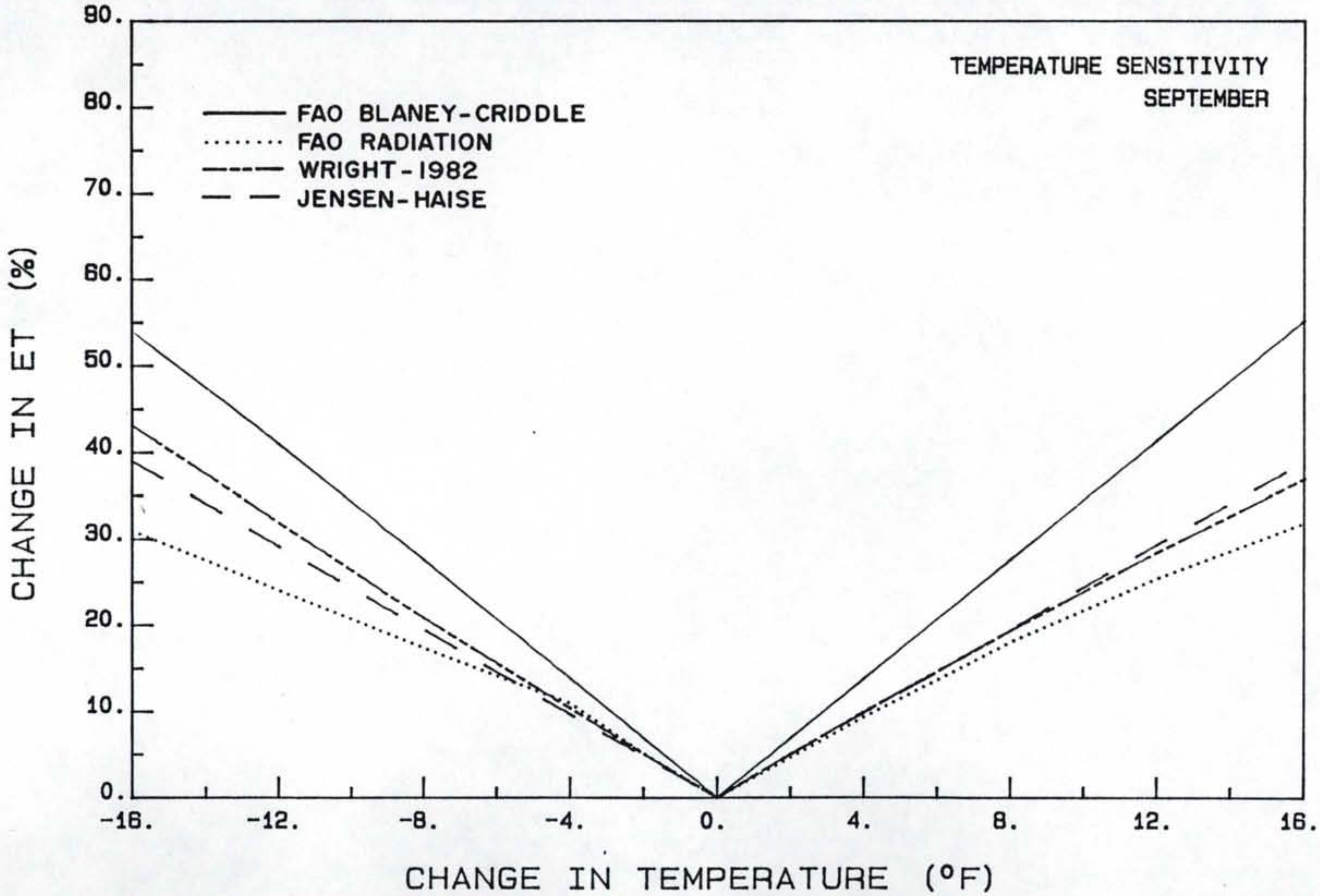

Figure A-6. Temperature sensitivity for September, Kimberly, Idaho.

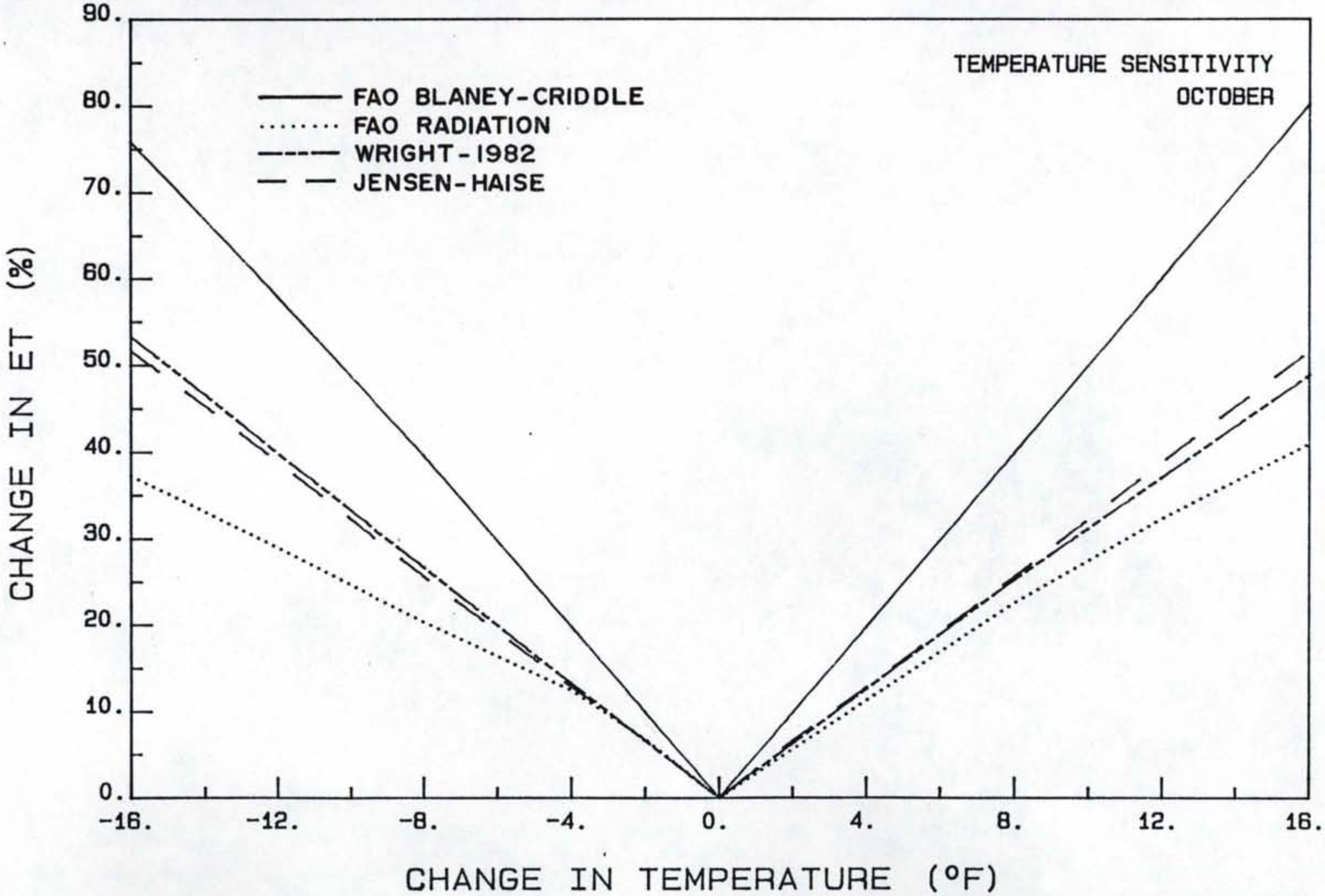

Figure A-7. Temperature sensitivity for October, Kimberly, Idaho.

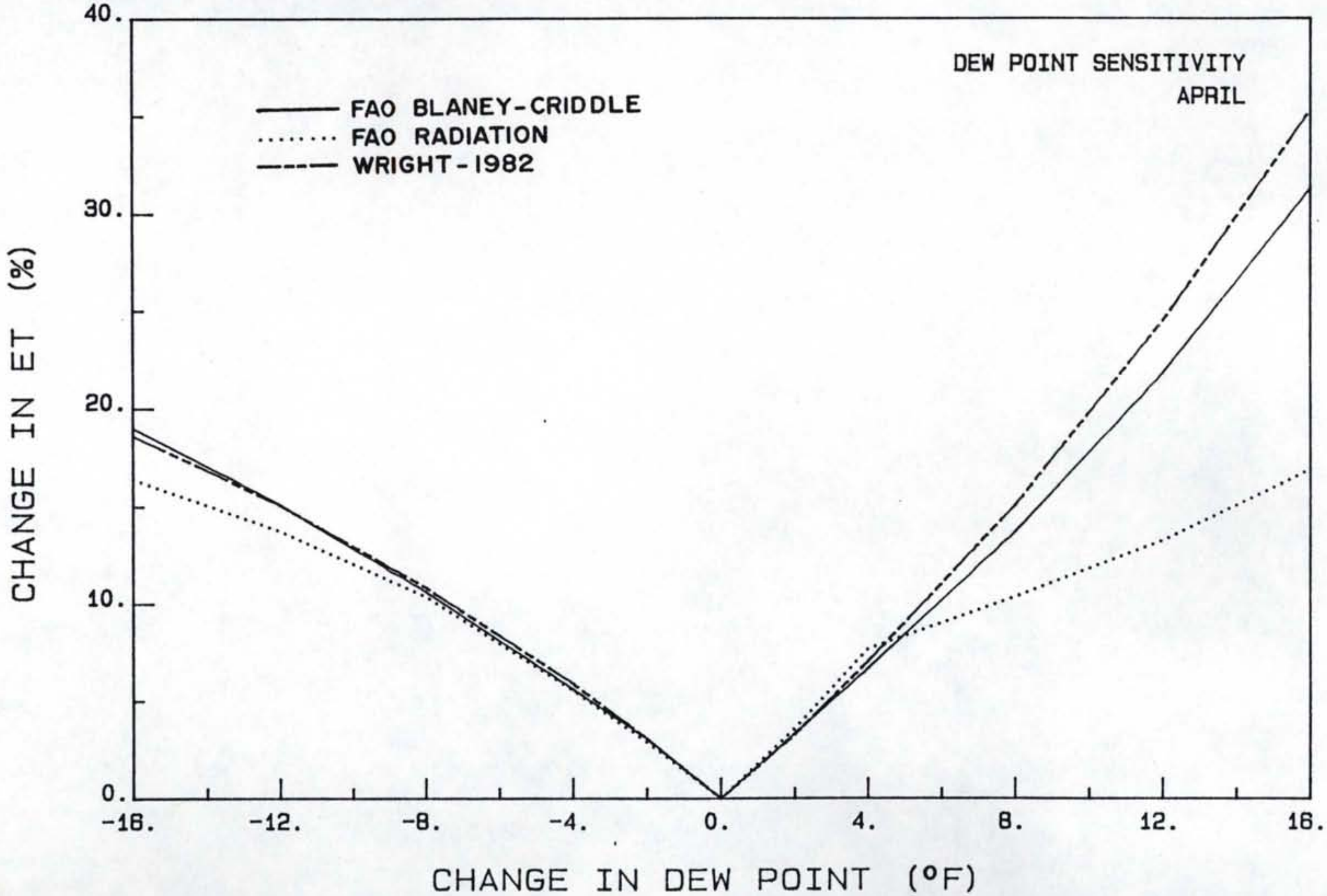

Figure A-8. Dew point sensitivity for April, Kimberly, Idaho.

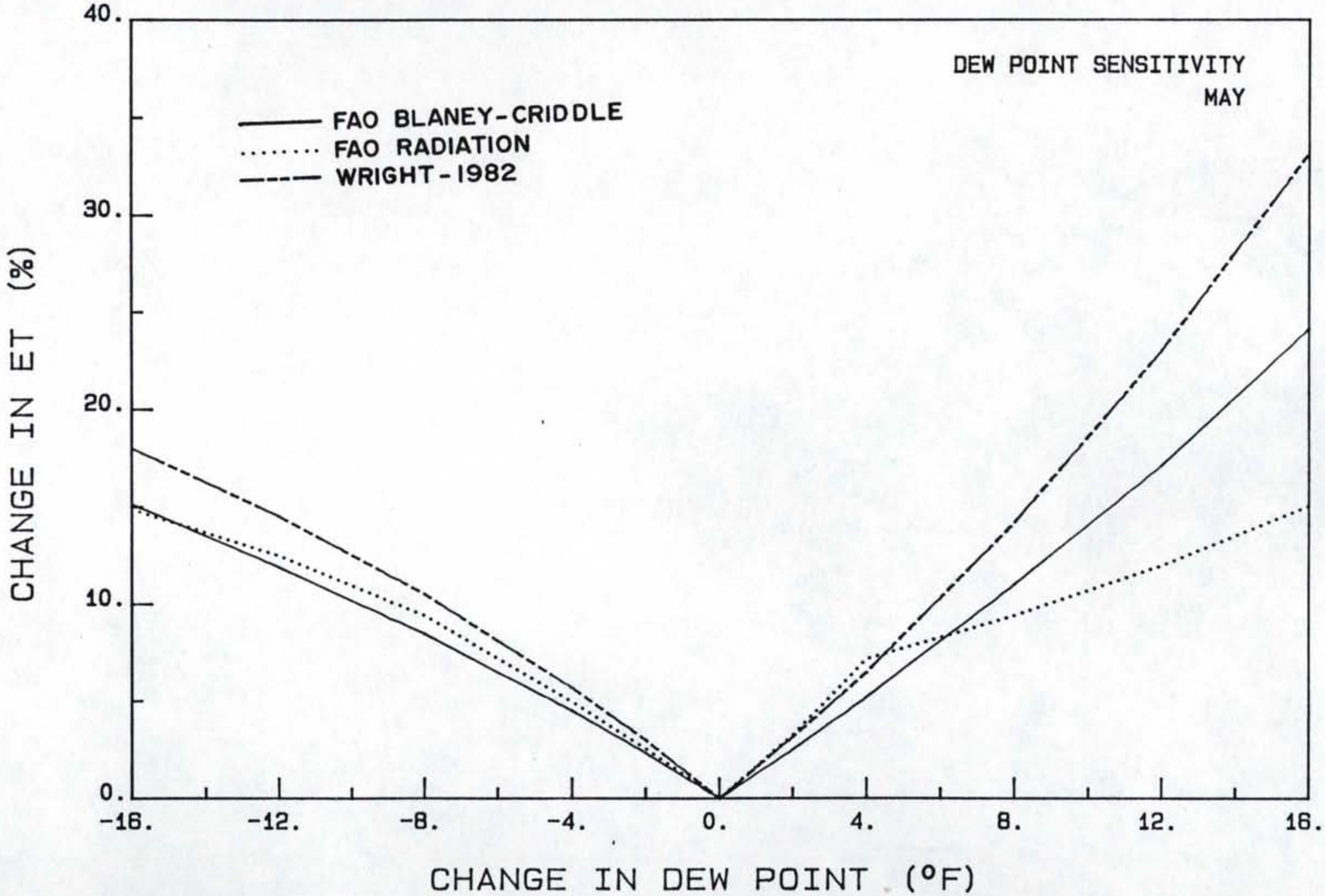

Figure A-9. Dew point sensitivity for May, Kimberly, Idaho.

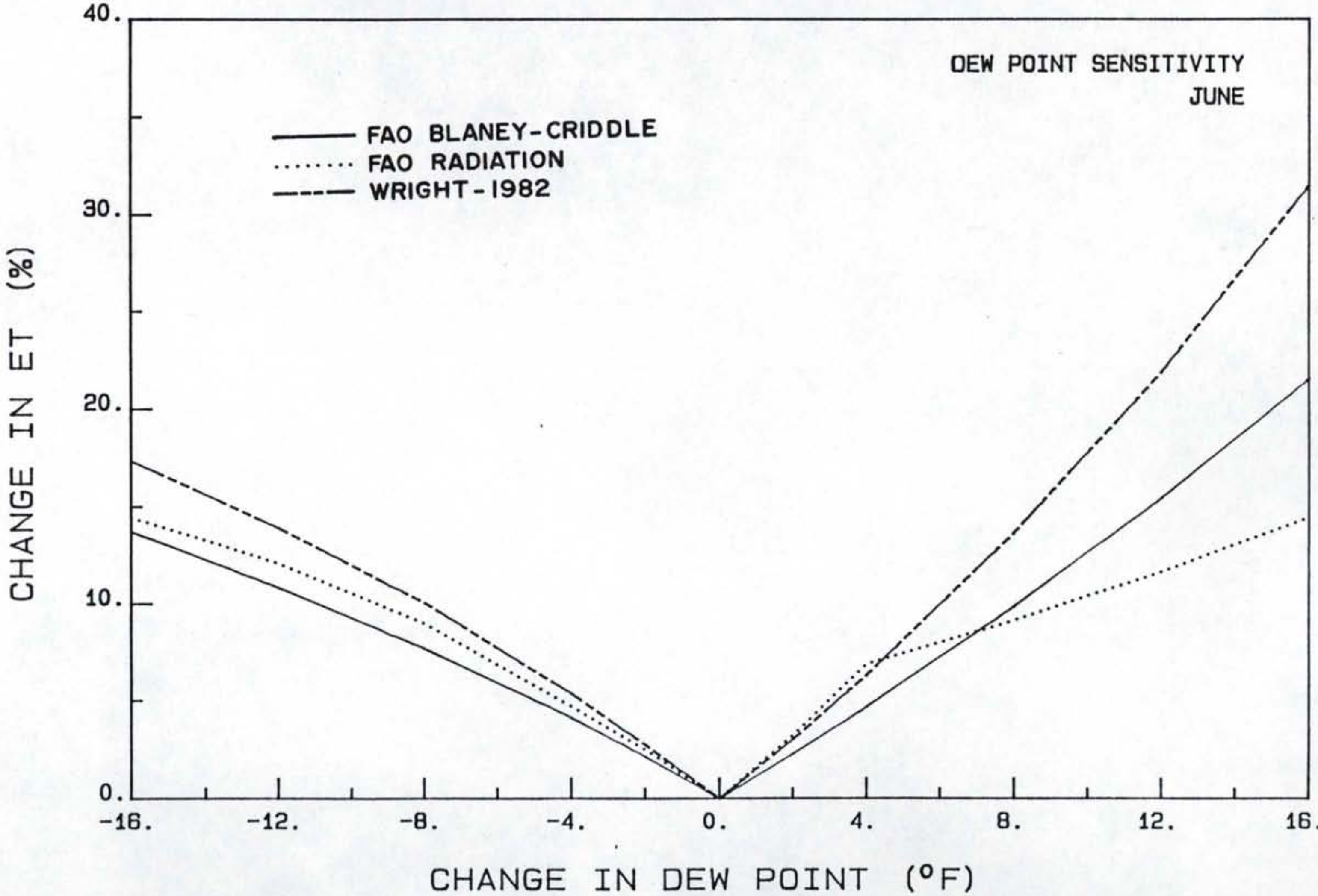

Figure A-10. Dew point sensitivity for June, Kimberly, Idaho.

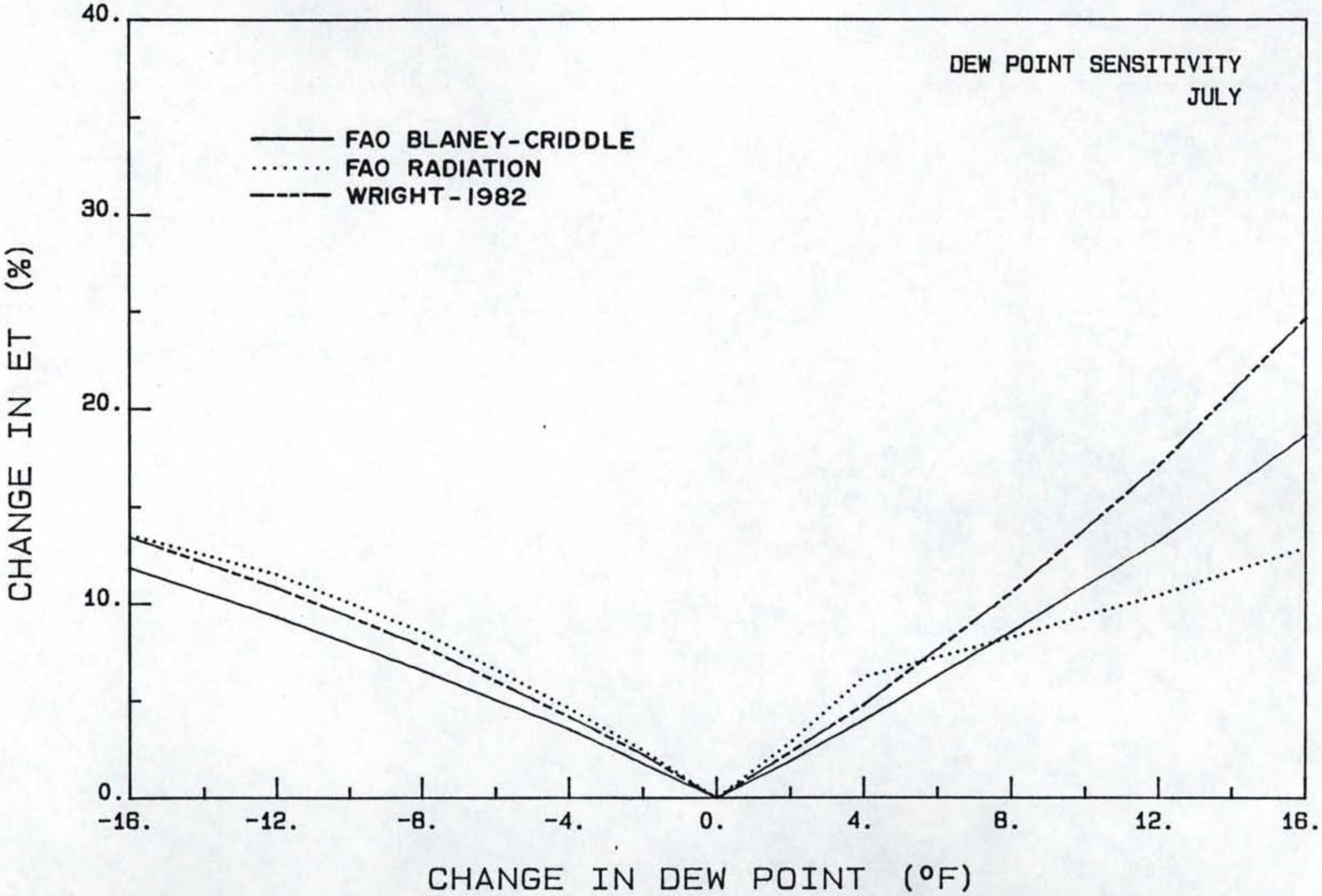

Figure A-11. Dew point sensitivity for July, Kimberly, Idaho.

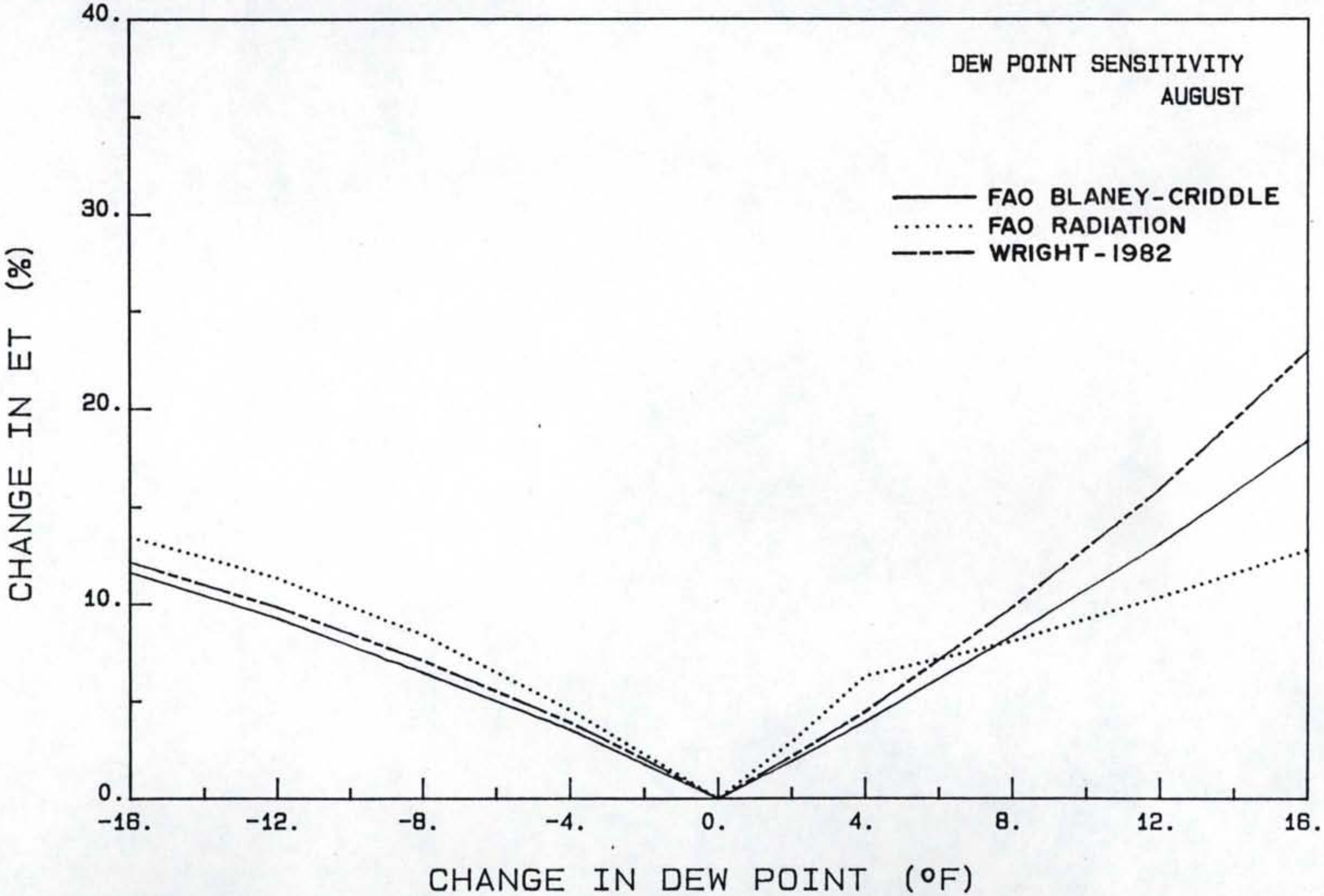

Figure A-12. Dew point sensitivity for August, Kimberly, Idaho.

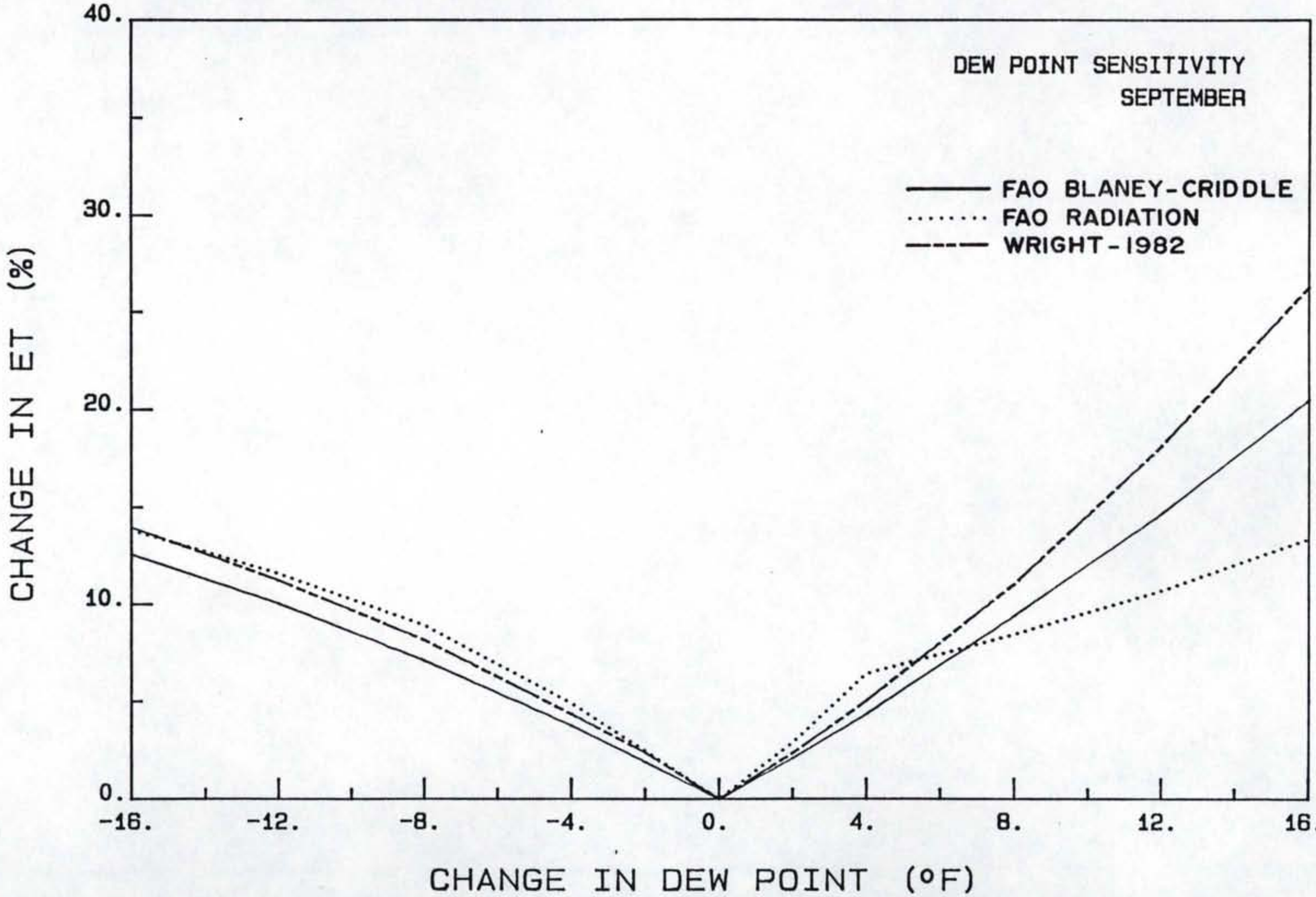

Figure A-13. Dew point sensitivity for September, Kimberly, Idaho.

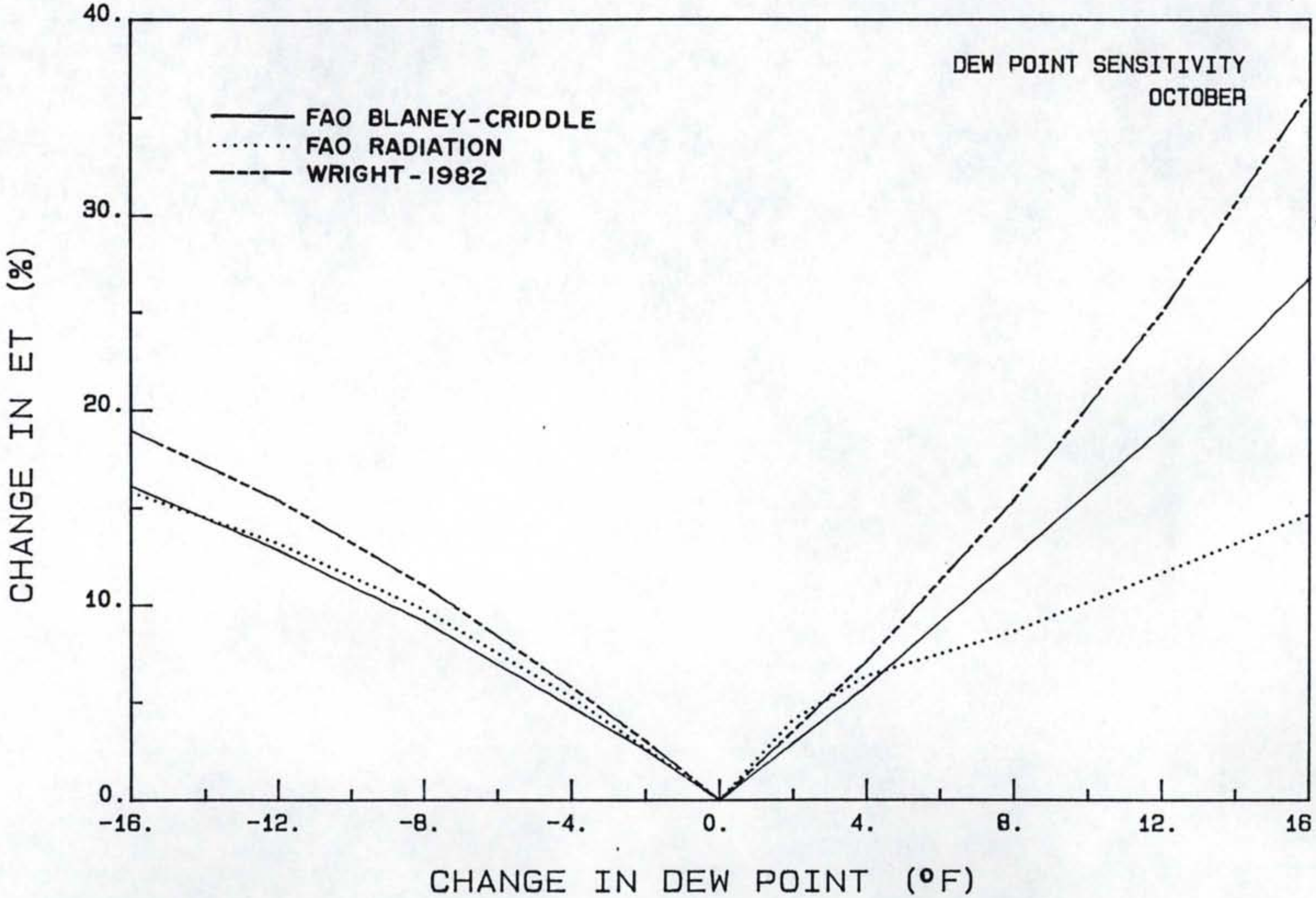

Figure A-14. Dew point sensitivity for October, Kimberly, Idaho.

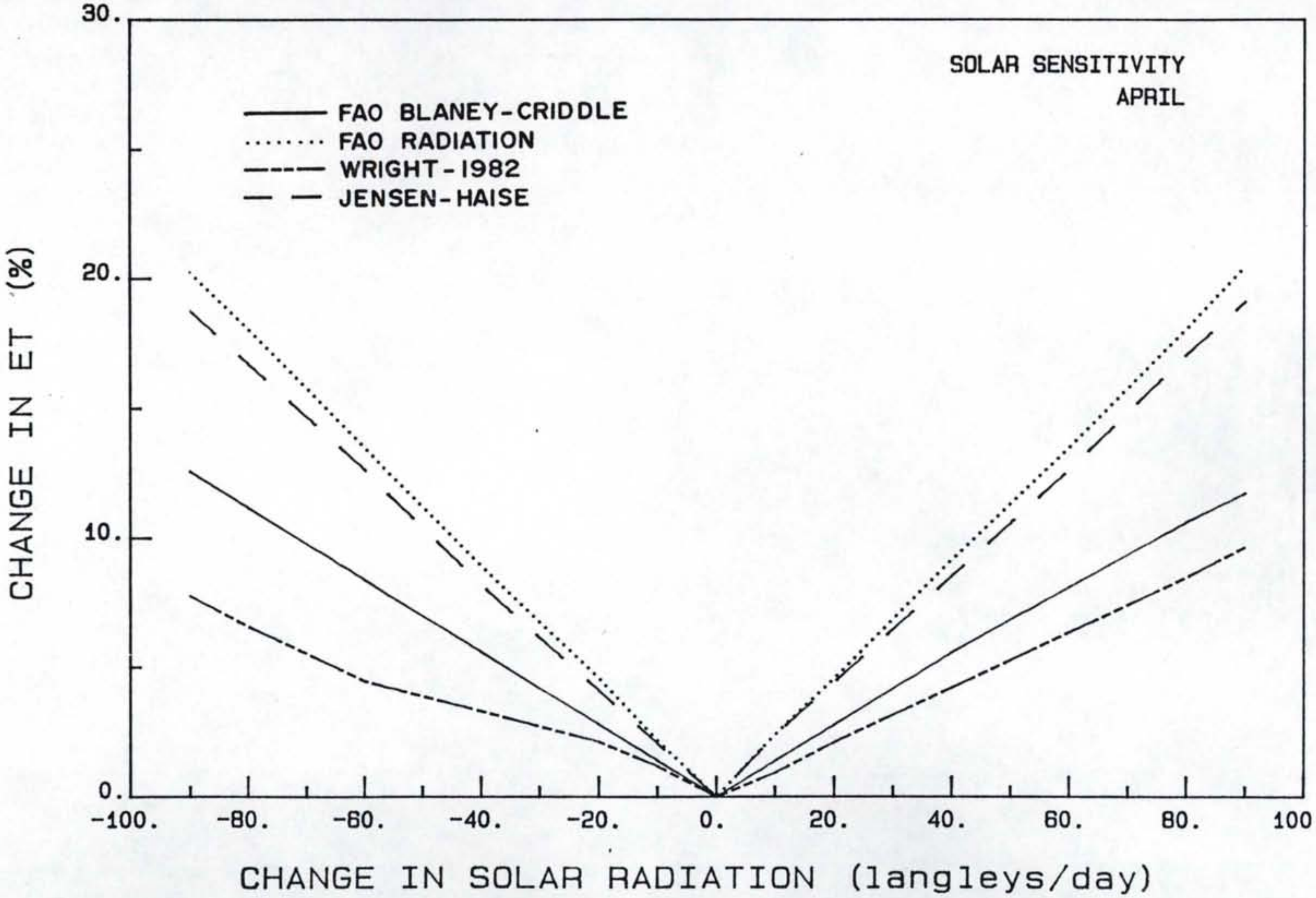

Figure A-15. Solar sensitivity for April, Kimberly, Idaho.

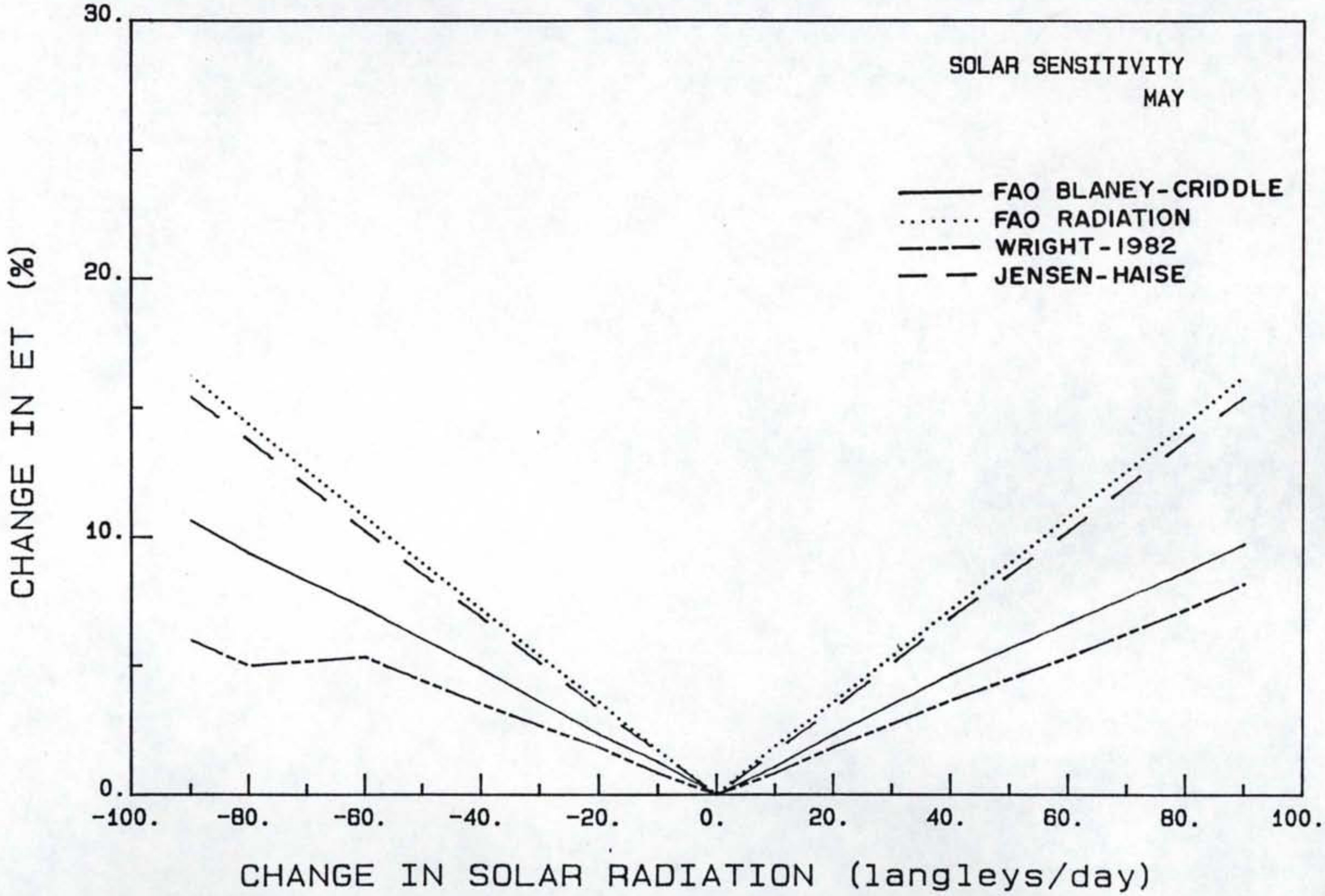

Figure A-16. Solar sensitivity for May, Kimberly, Idaho.

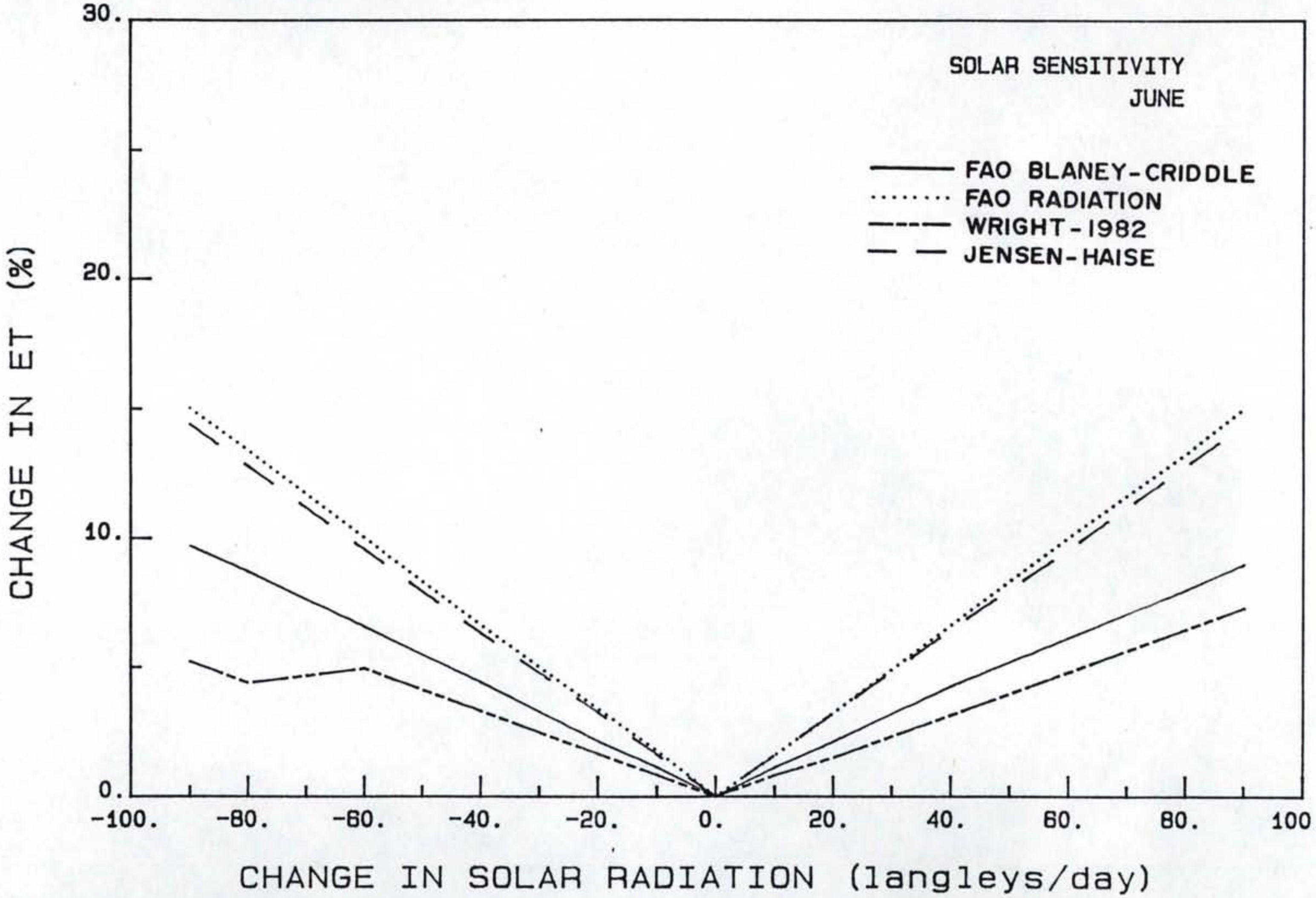

Figure A-17. Solar sensitivity for June, Kimberly, Idaho.

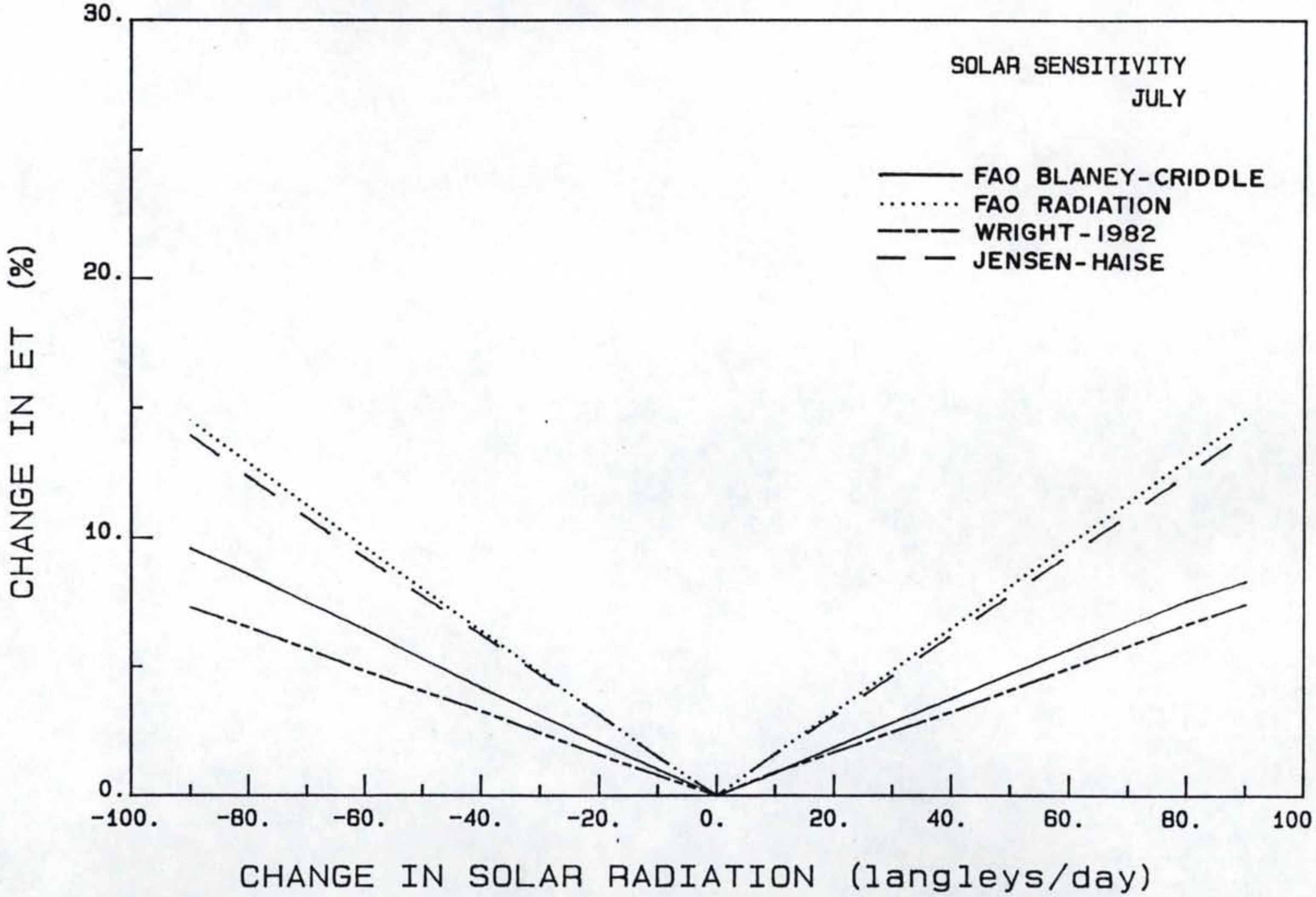

Figure A-18. Solar sensitivity for July, Kimberly, Idaho.

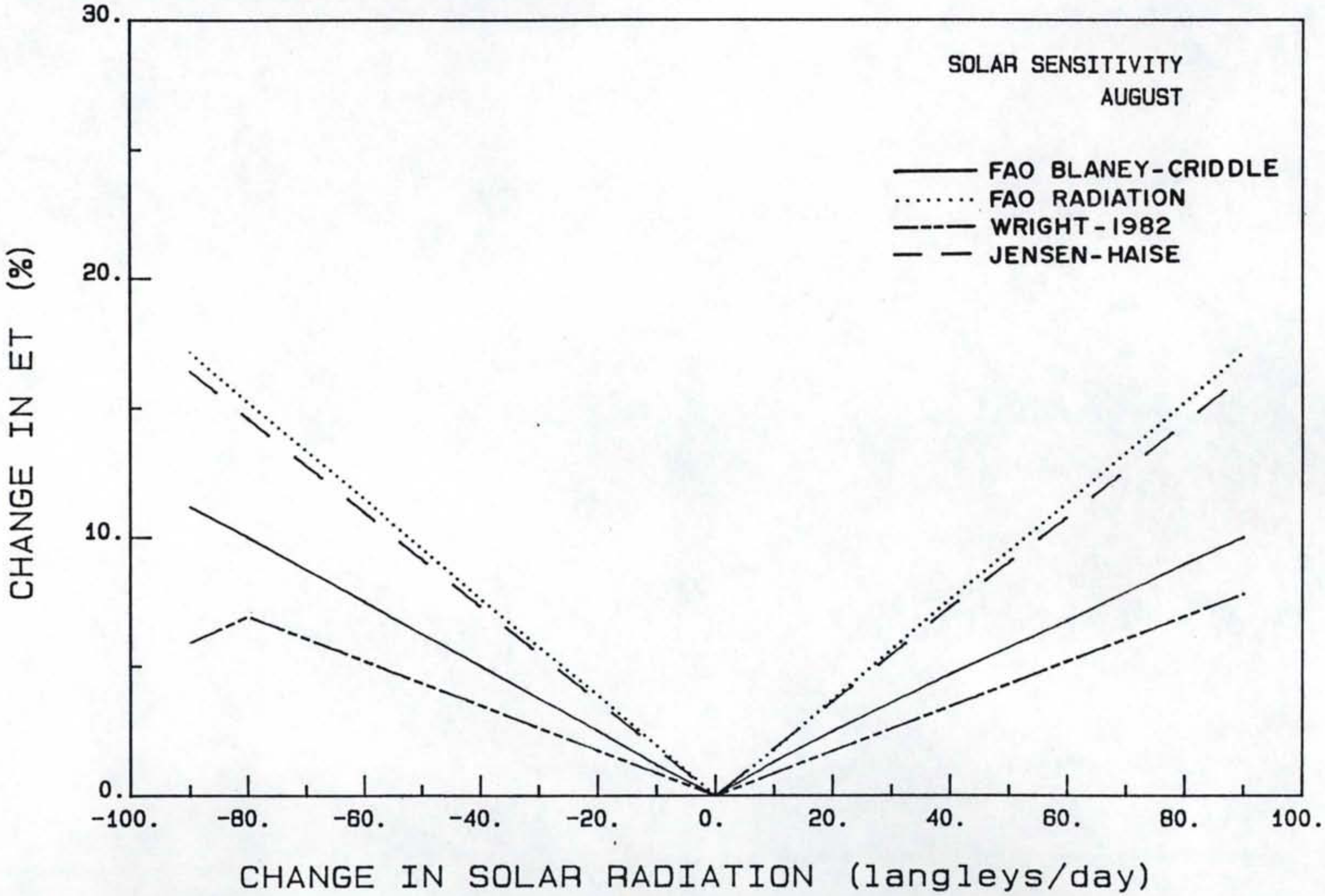

Figure A-19. Solar sensitivity for August, Kimberly, Idaho.

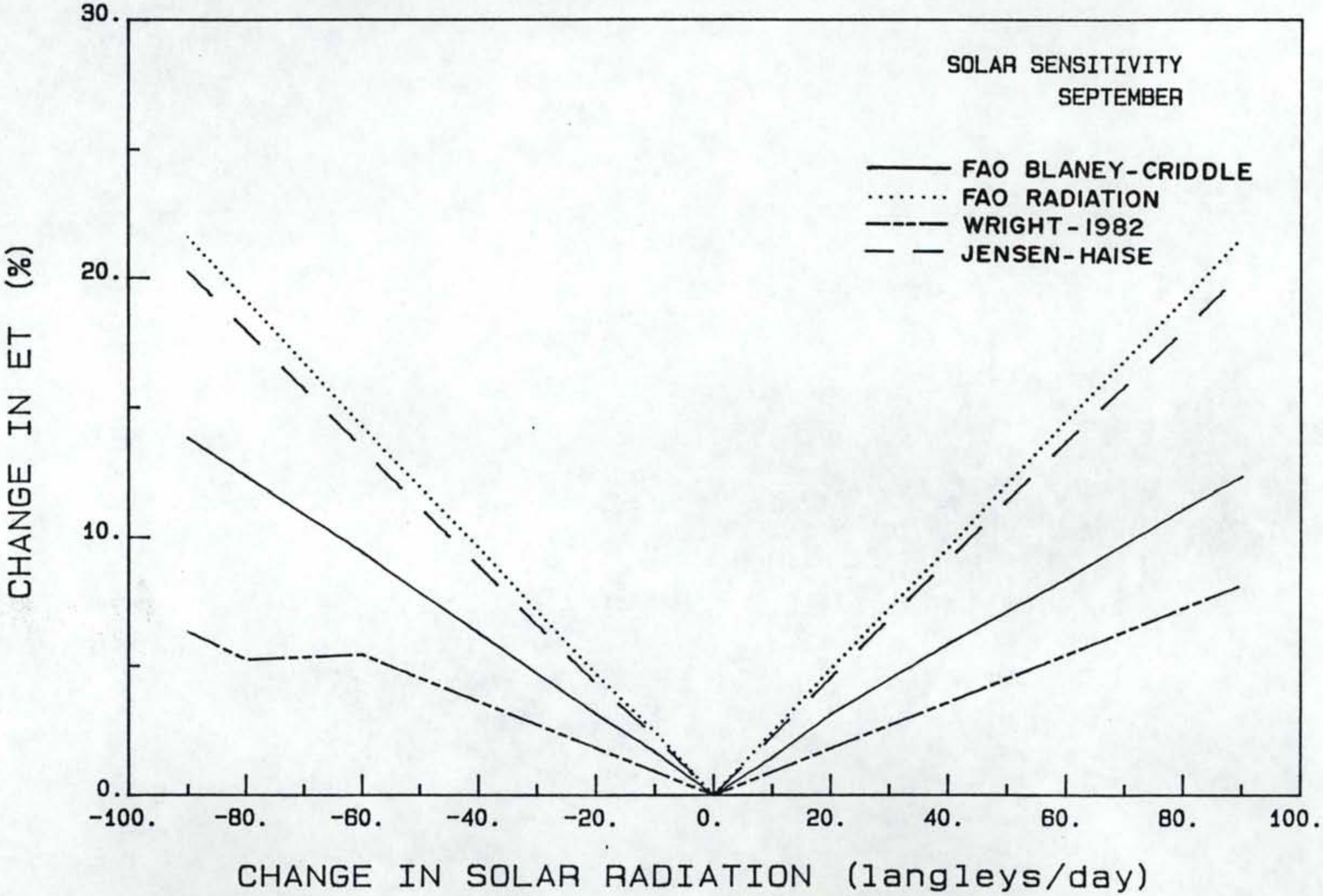

Figure A-20. Solar sensitivity for September, Kimberly, Idaho.

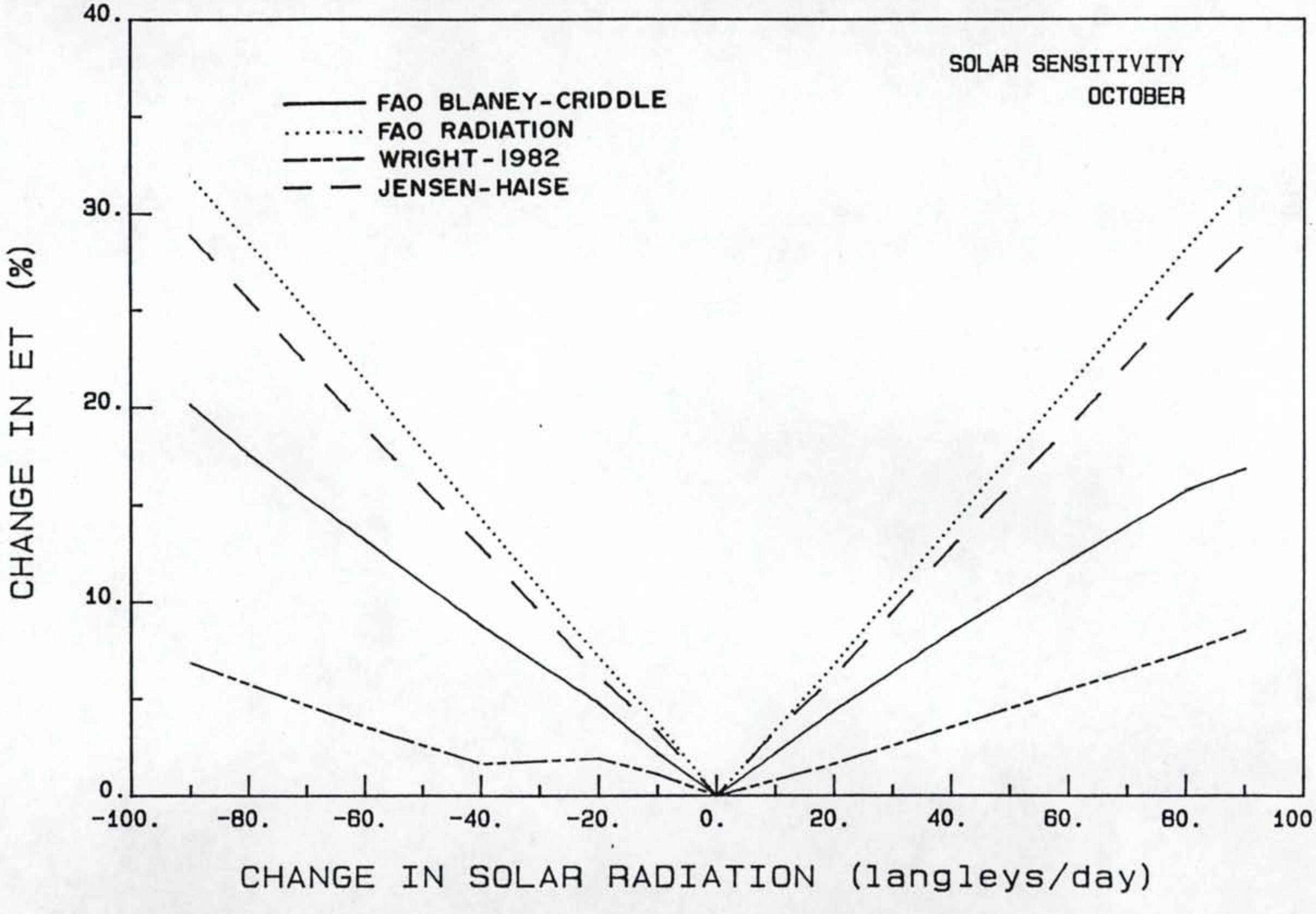

Figure A-21. Solar sensitivity for October, Kimberly, Idaho.

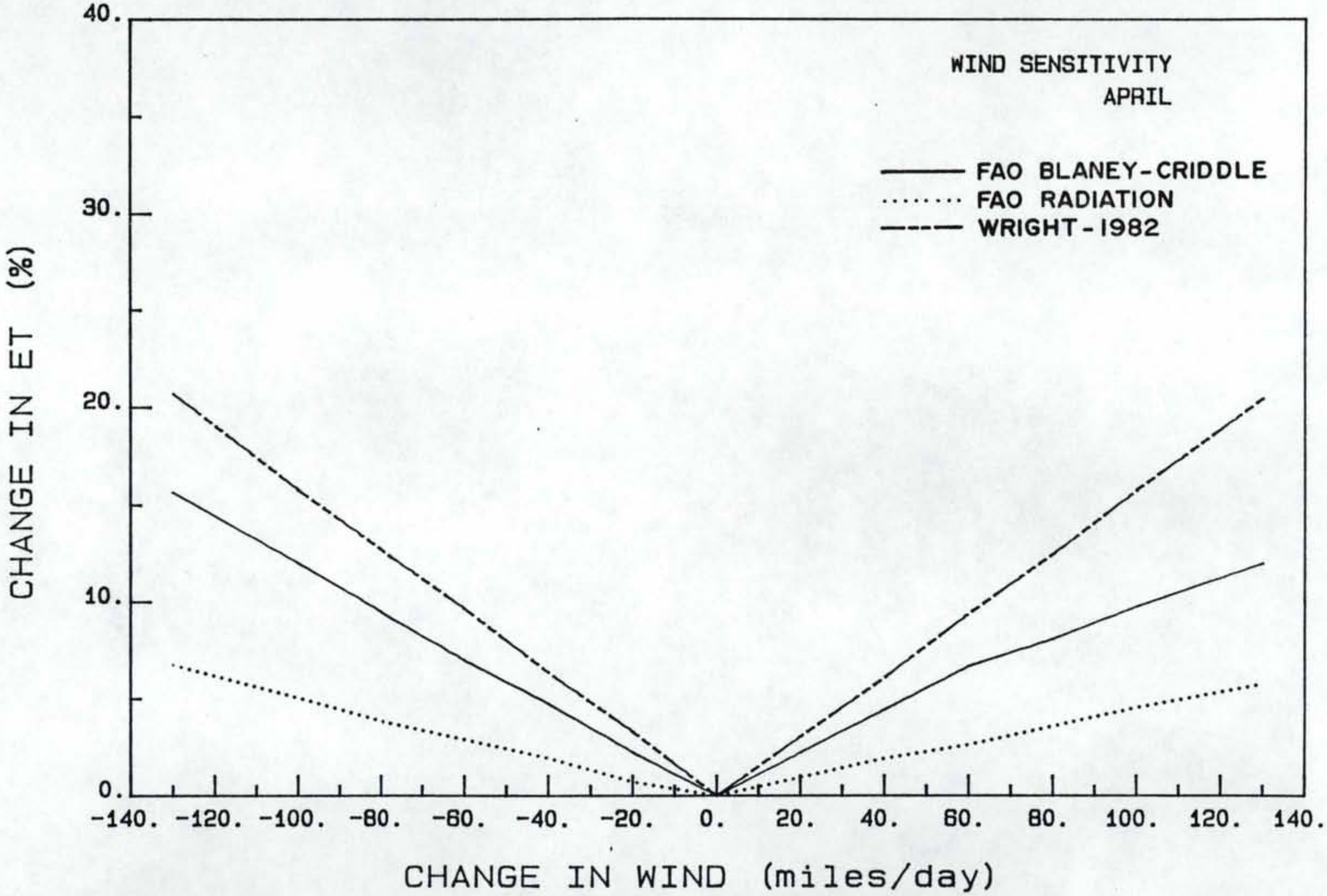

Figure A-22. Wind sensitivity for April, Kimberly, Idaho.

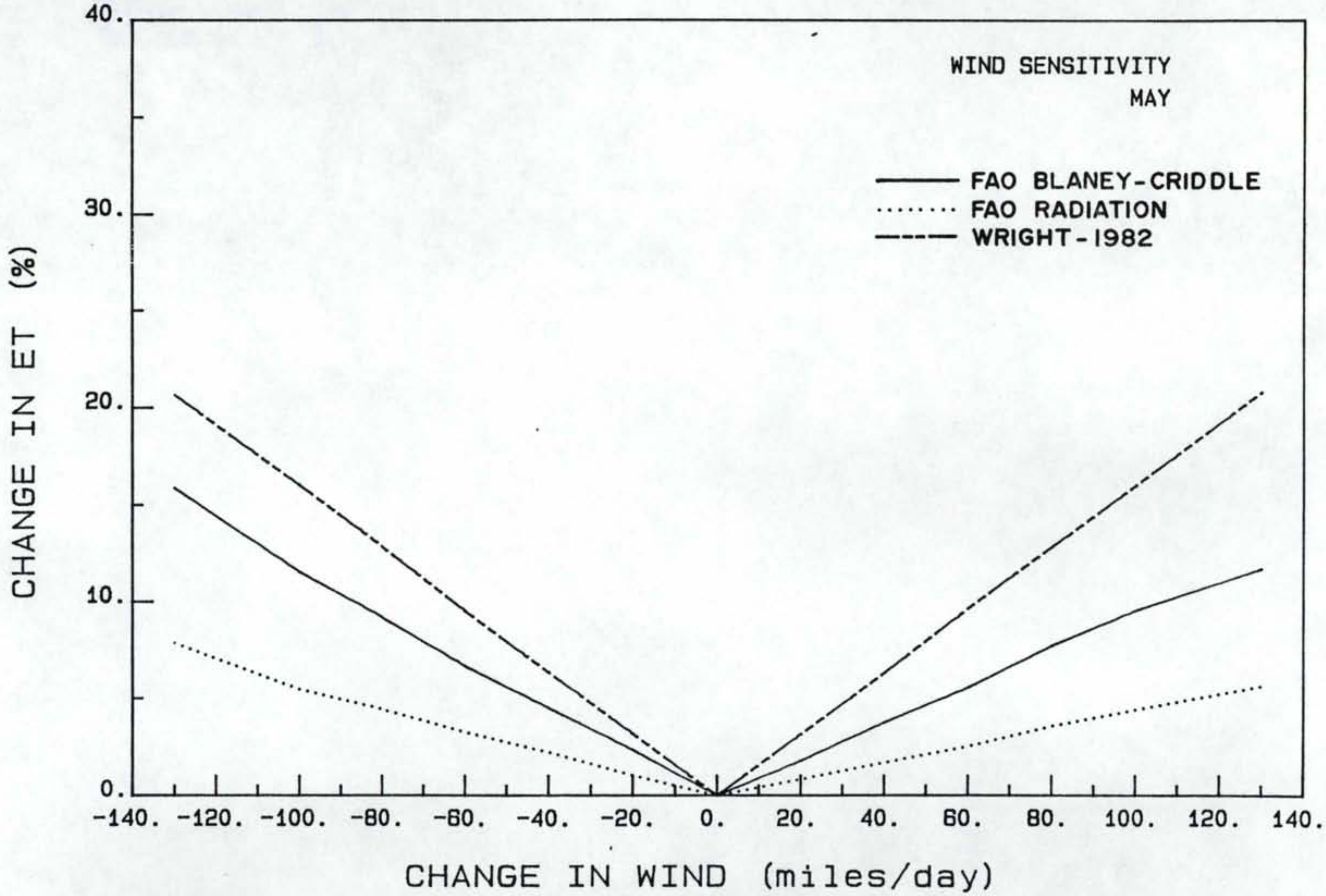

Figure A-23. Wind sensitivity for May, Kimberly, Idaho.

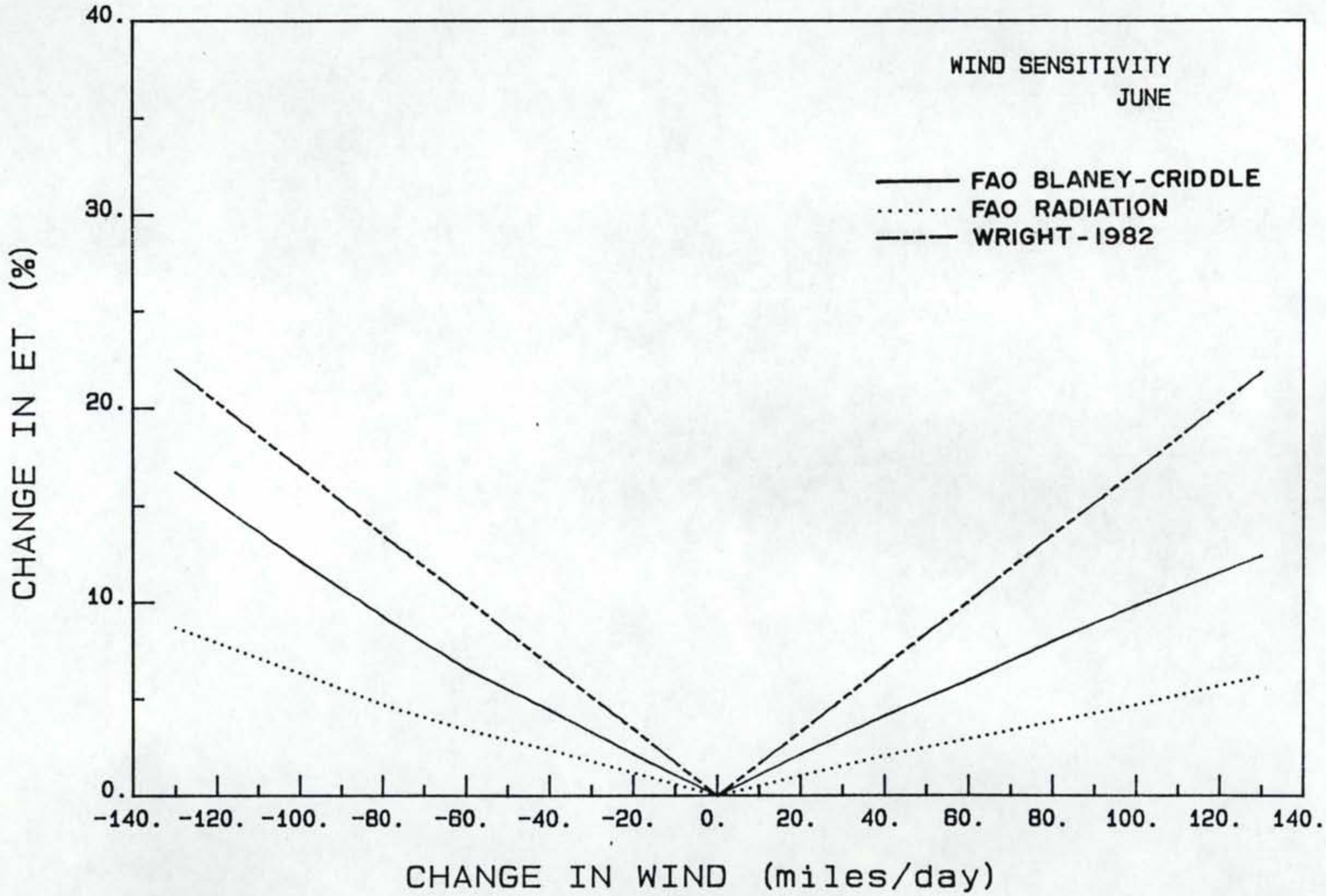

Figure A-24. Wind sensitivity for June, Kimberly, Idaho.

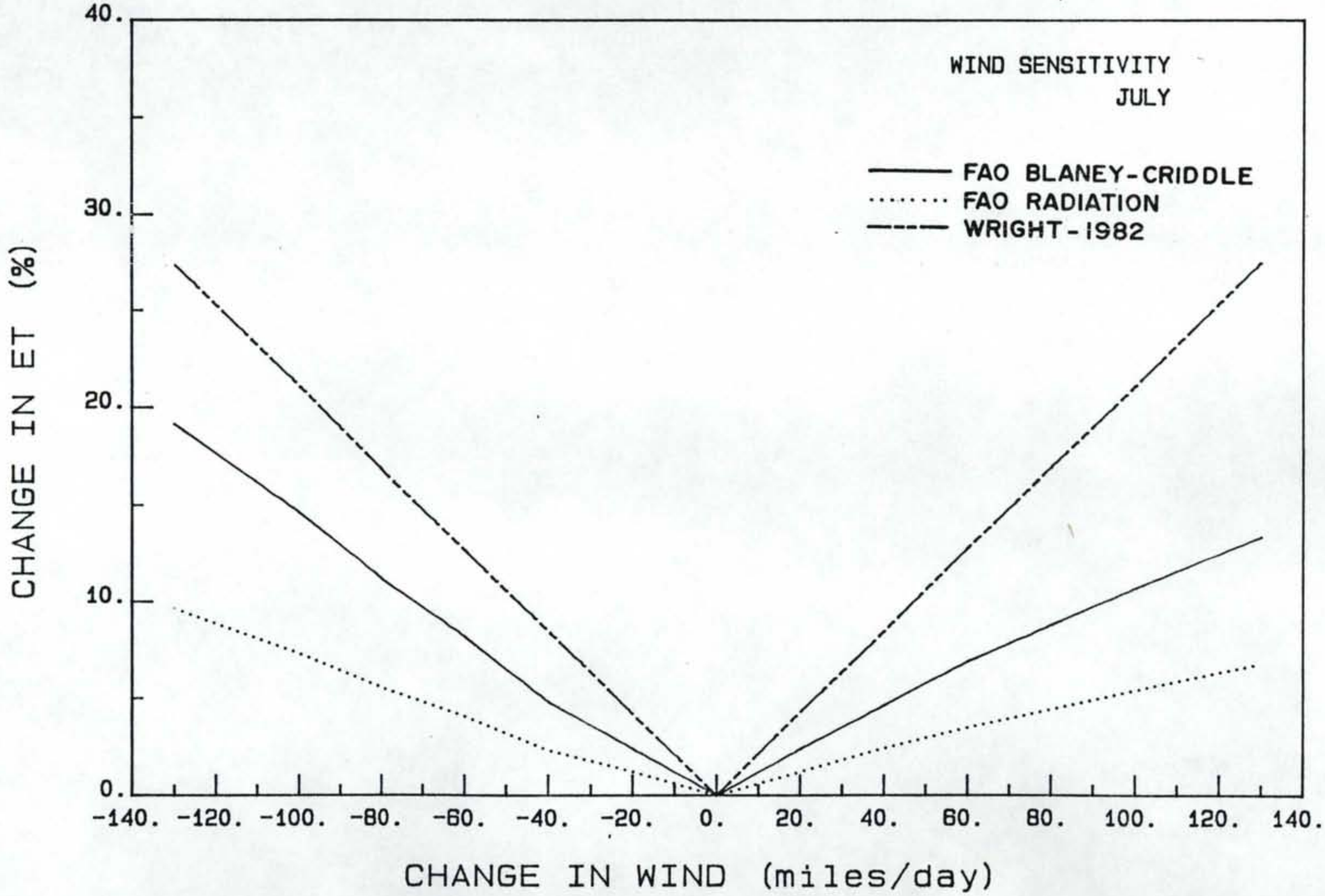

Figure A-25. Wind sensitivity for July, Kimberly, Idaho.

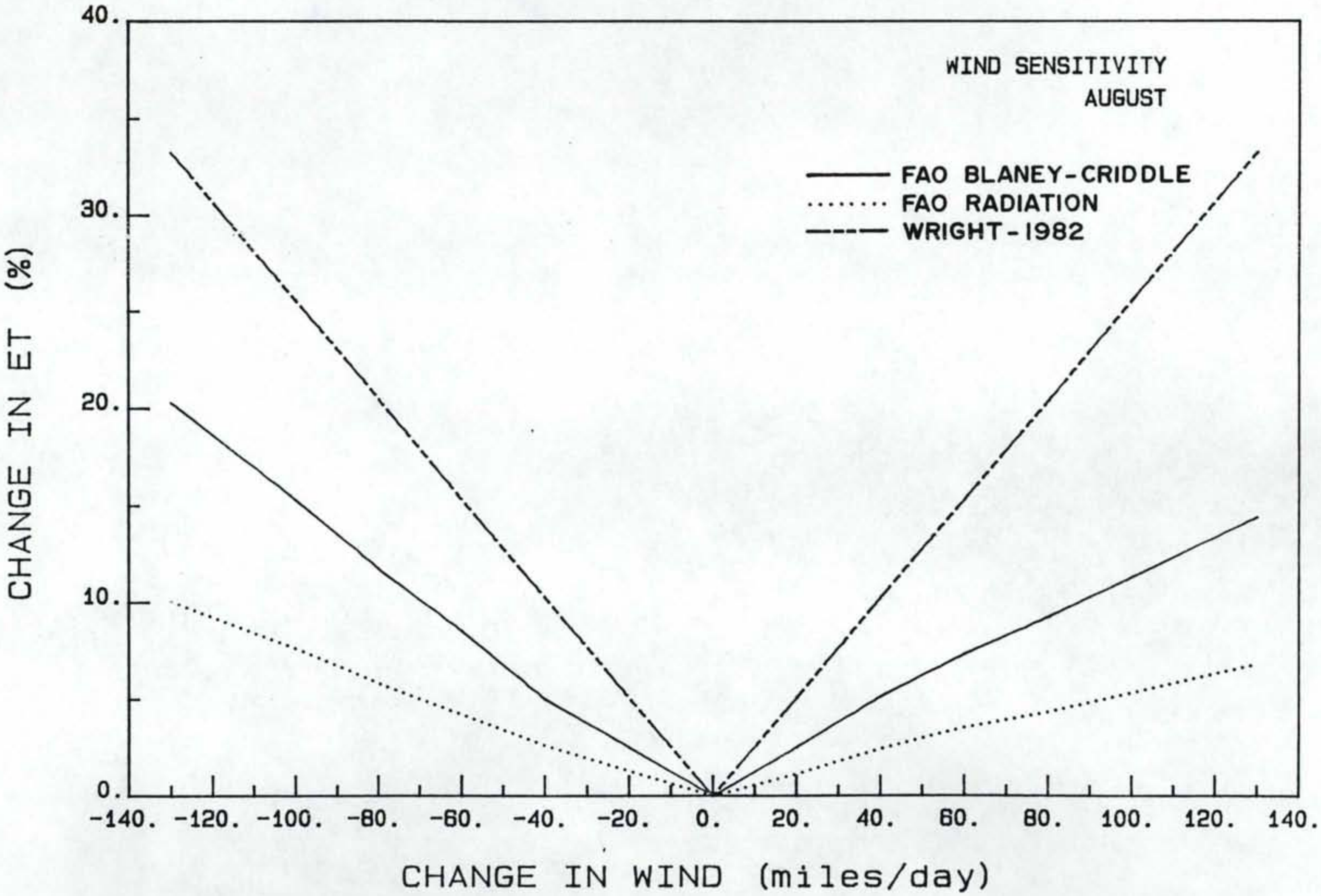

Figure A-26. Wind sensitivity for August, Kimberly, Idaho.

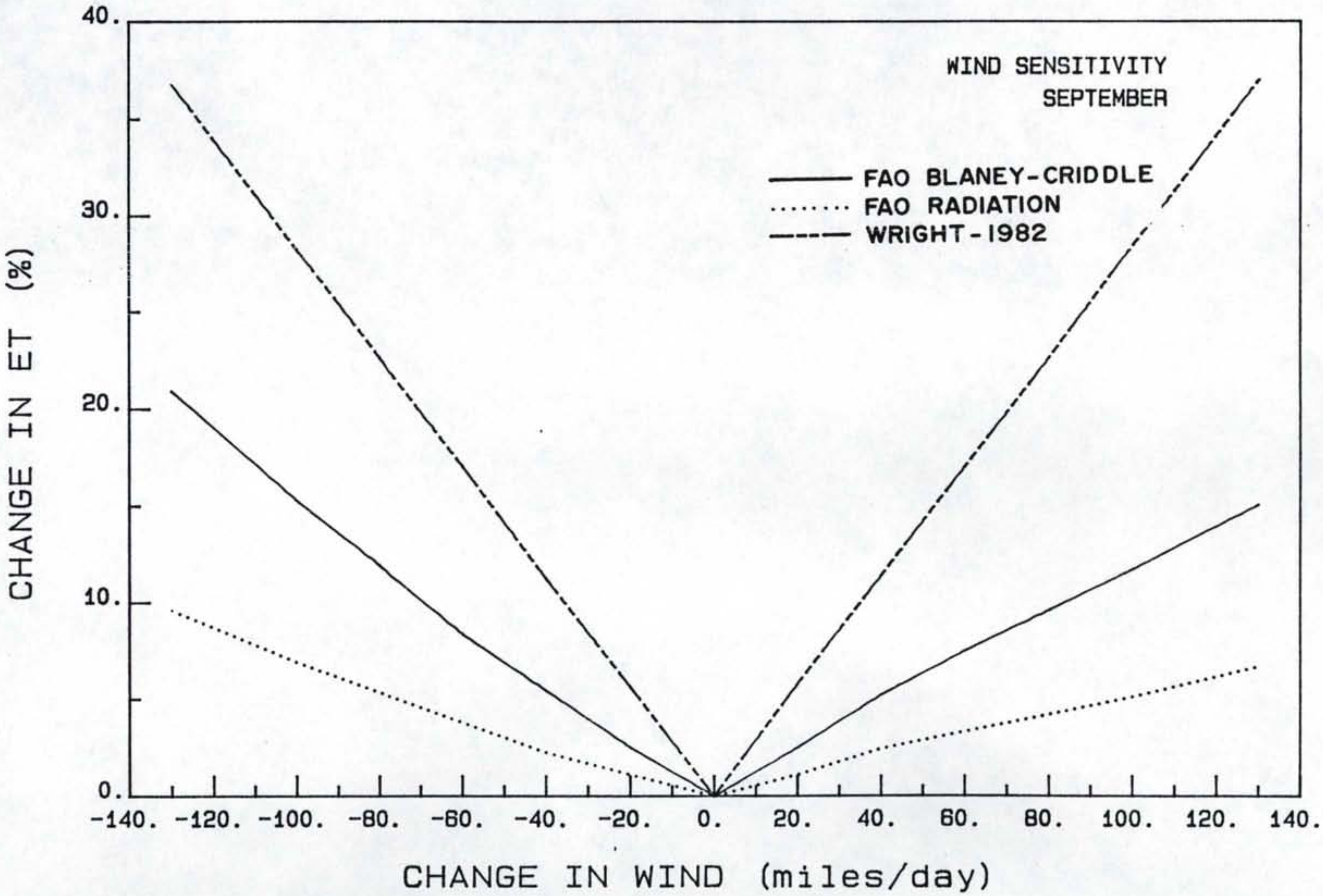

Figure A-27. Wind sensitivity for September, Kimberly, Idaho.

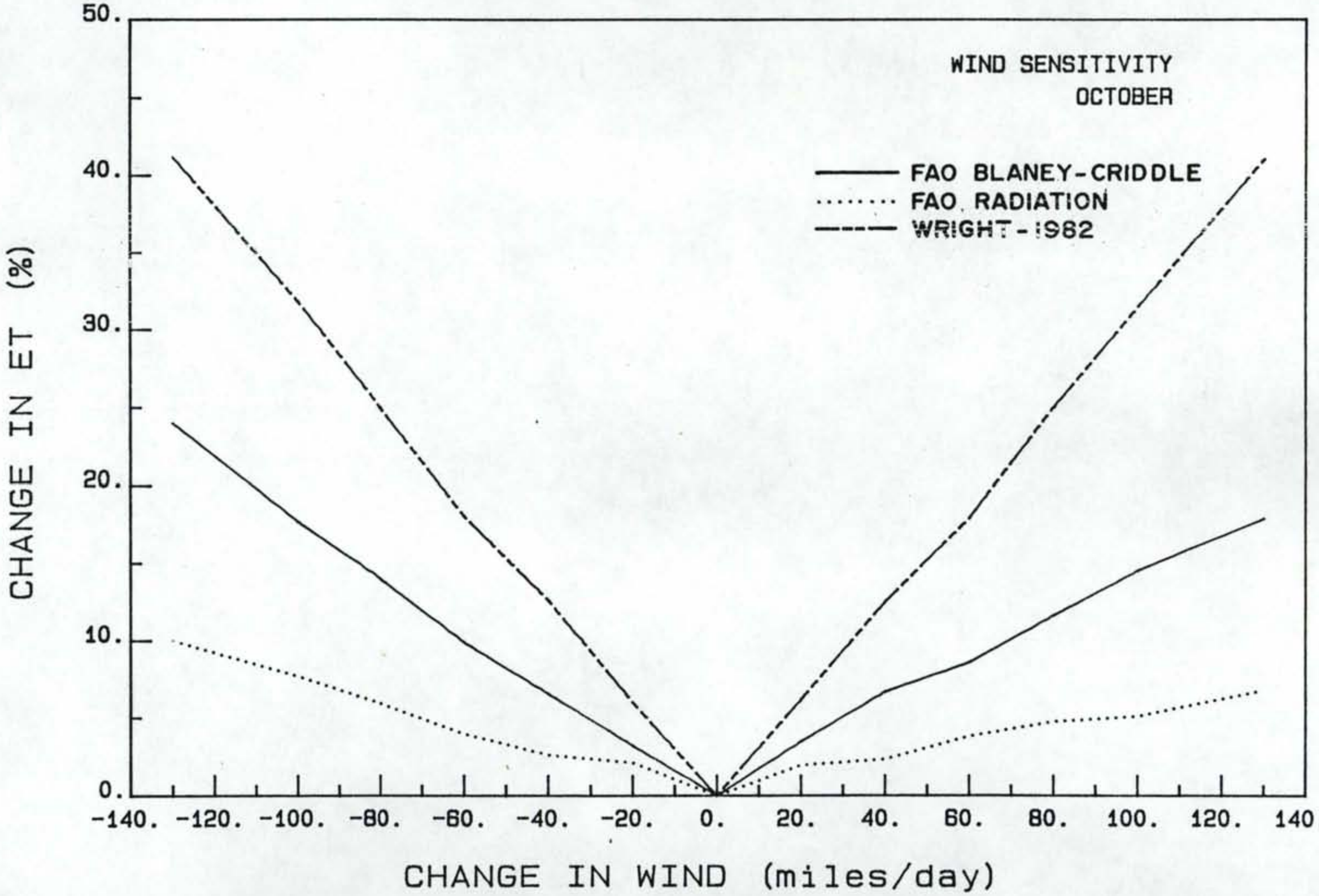

Figure A-28. Wind sensitivity for October, Kimberly, Idaho.