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A CLIMATE-BASED MODEL FOR MAXIMUM YIELDS FROM RAIN-FED CROPS IN MALI

by

Steven L. Woodall

Prospectus

This document is the final report of the author's consultation*, under the sponsorship of the U.S. Agency for International Development, with GRM's Projet Inventaire des Ressources Terrestres, or PIRT. The report stands alone in defining the context of a computer model, in describing its conceptual development, and in giving step-by-step instructions on its use; the three parts of the report correspond to those three objectives. References to literature follow Part II, followed immediately by several appendices. Part III consists mostly of attachments of computer printed material.

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*Covering the period 9 September-9 November, 1985.

PART I

Why Another Model?

PIRT's present work consists of the inventory and mapping of Mali's physical resources and ultimately the assessment of 'best land use' for each of the mapped land units. The highest priority land use for those units capable of supporting it is the cultivation of row crops. PIRT thus needs an objective means to determine which units can support intensive pluvial agriculture and, of those, which ones are the better and which ones are only marginal.

Two basic factors that differentiate among mapping units (zones) are climate and soil. In Mali's climate, where moisture availability is the factor most limiting agricultural productivity, we can restrict our attention initially to those climate and soil features that relate directly to moisture availabilty: seasonal rainfall and its daily distribution, seasonal evaporation and its distribution, and each soil's ability to store and release moisture. A realistic index of moisture availability for a growing crop cannot be a simple climatological one; the timing of rain and evaporation are frequently more important than total amounts, and evaporation rates are not independent of rainfall. When one chooses to evaluate more than one crop, one must also recognize that not all crops transpire at the same rate when well supplied with water, and that crops vary substantially in their ability to extract moisture from 'dry' soils.

The most obvious index of the suitability of a given zone for a particular crop is crop yield itself. One may argue that, during the centuries of Mali's occupation by agrarian people who cultivated, then as now, such crops as millet, sorghum, cowpeas, and bambara groundnut, all the zones suitable for sedentary, rain-fed farming of these crops were discovered and settled, and those found unsuitable were quickly abandoned. Nevertheless, perhaps Mali's arable land base can be expanded through the identification of zones that native farmers have wrongly rejected, and thus for which no yield data exist. The logic of using yield as an index of the integrated effects of climate and soil is strong, even when inadequate empirical data forces us to fall back on theoretical estimates.

PIRT has been committed, from its inception, to a quantitative, theoretical approach to land suitability assessment, which implies the use of climate-based crop yield models.

Related Past Work at PIRT

The tangible product of PIRT's first years of existence (th TAMS years) is a set of reports, in three volumes, released i 1983. The third volume, which contains as annexes the conceptua and logistical bases for the conclusions presented in volume (maps) and volume II (technical report), is the volume o interest here and will be referred to here after as 'TAM (1983)'. [Relocating material in the annex volume is difficul since page numbers are missing, and since some material i repeated four times due to French and English translations; th reader must be satisfied by my ambiguous references to whol annexes.]

Annex B5 (TAMS, 1983), presents estimates of mean monthl potential evapotranspiration for those 17 stations in Mali's synoptic meteorology network for which the length of record was good. An updated version of the widely-used formula of Penmar (1948), as described by Doorenbos and Pruitt (1977), was the basis for the calculations. My spot checks confirmed that TAMS's consultant hydrologist, Mr. J.C. Henry, used without modification the computer program provided on pp. 120-130 of Doorenbos and Pruitt, choosing the corrected Penman option and inputting the following: mean air temperature, mean relative humidity, mean sunshine hours, mean 24-hr wind run, and day/night wind ratio. Tables 1.4 and 1.10 (maximum relative humidity and number of rainy days) are superfluous. Mr. Henry wisely refrained from further modifying the corrected Penman equations for Malian conditions, in that the utility of potential ET estimates primarily depends on the standardization of their calculation. Thus, Mr. Henry's estimates should be fully adequate for PIRT's inventory activities.

In Annex B2, TAMS combined the ET estimates described above with the rainfall record at each station to derive a seasonality index named "length of growing season." The technique used was an adaptation of one that has been a standard for agroclimatological classification within the semi-arid tropics for two decades (Cochemé, 1966; Cochemé and Franquin 1971), although it is criticized in the excellent new publication by Sivakumar et al (1984). The early definition was simple: the growing period is the period during a year when precipitation continuously exceeds 0.5 * ETP, plus that period required to evapotranspire, at the full potential rate, any residual soil moisture, the latter defined as rainfall exceeding full ETP and limited to a maximum of 100 mm. TAMS's enhancements to this definition are quite involved, but are adequately described in Annex B2. The index cannot be calculated for individual years, since rainfall typically passes across the ETP threshold several times during the actual growing season. Consequently, mean annual rainfall curves for each station were utilized. Insofar as TAMS adopted a sufficiently sophisticated indexing approach, and insofar as it used good ET estimates and a long (30+ years), properly-editted rain record, the work of calculating growing season duration in

Mali should be considered finished-- and Map 1, at the end of Annex B2, which gives interpolated isolines of growing season duration, should become a basic reference. The index should not be interpreted literally, however-- certainly not as an absolute time frame for rainfed cultivation of a wide range of crops. Its strength is in its simplicity, so further efforts to develop a more realistic index are to be discouraged. In particular, I suggest that the other, more complex, map of growing season duration (also labelled Map 1, but found at the end of Annex B3) be ignored; its use can only lead to misinterpretation, especially since it is at odds with the first Map 1.

Annex B3 of TAMS (1983) describes the climate-based crop yield (agroclimatological) model developed by another TAMS consultant, Mr. J. Albrecht. His model monitors the soil water balance on a daily basis for individual years of record and adjusts estimates of daily photosynthesis in response. The basis for his potential photosynthesis submodel was purportedly the work of De Wit as discussed in Kassam (1978). I have not located in Bamako the relevant works by De Wit, but believe to have found the work of Kassam-- under a different author and title (FAO, 1978). The relationships between Albrecht's model and that of FAO (1978) are not clear, while the deviations are prominent. In particular, Albrecht's model estimates daily values of photosynthesis (or growth) each day in the crop's lifetime, while FAO's makes a single estimate at the midpoint of the crop's growth period. Unfortunately, there now exists at PIRT no other documentation of the Albrecht model other than Annex B3. Although the voluminous output of the computer program [PIRT #1270] is available in the Documentation Center, a listing of the program itself is not. There are a number of important details that cannot be reconstructed from Annex B3, including the way in which growing season duration is calculated for those cases where soil moisture remains available after the crop is supposedly harvested. Despite the importance placed on the estimation of growing season duration by the Albrecht model, the ambiguity of its definition renders the estimate uninterpretable. Were enough time available to me to permit direct communication with the model's author, all these documentation problems could, of course, have been remedied.

After the end of the TAMS involvement and at the initiation of its current zonage work, PIRT realized that it still needed a computer model that it could operate in-house, for an expanded number of candidate species and site descriptions. Obviously uncertain (as I am) about the exact nature of the Albrecht model, PIRT is nevertheless committed to its basic approach. Therefore, my assignment became to improve the 'existing' model while making possible its routine use by PIRT staff.

As the Albrecht model did not effectively exist and available documentation was insufficient to guide its duplication, I developed a new model which borrows heavily from FAO (1978) for the estimation of constraint-free yields, and which appears to have a simpler water balance submodel than the Albrecht model. I

strongly suggest that the reader become familiar with the FAO document before approaching Part II of the present report. That document, although debatable in its details, is a good example of how theoretical crop yield estimates can be incorporated into agricultural zoning activities at a national, or even regional, level.

Model Application

The model is highly theoretical and somewhat unverifiable, so any similarity between predicted and actual crop yield on a given site is coincidental. The model's purpose is not to predict absolute yields accurately, but to classify, or rank, sites. Once again, crop yield is used as a surrogate for the site's agroclimate, in recognition of the difficulty of otherwise quantifying the latter.

Indexing does not, however, remove all risk of making a false prediction. Let's assume that three classes were adequate for the determination of site suitability for a given crop: excellent, adequate, and poor. The model performs as hoped if, on the idealized diagram of Figure 1, all observations of predicted versus actual yields plot within the hatched blocks. The scales of the X and Y axes need not be the same, so the values separating the classes can only be chosen by skilled agronomists and agricultural economists exercising their professional judgements. The best and worst sites should be easy to detect; the intermediate ones will require more care.

Confidence attached to predictions of intermediate values depends on the degree to which the model has been calibrated and then verified. I have only partially calibrated the model, so have kept those parameters that are likely to be critical to the calibration as input variables, which makes them easy to change. Verification is a continuing task for serious users of any model. As empirical information on crop yield improves, opportunities improve for the verification and strengthening of this model. Three types of data will be needed, preferably in the following order.

First, the establishment of maximum constraint-free yields requires data on actual yields from small research plots which have received whatever cultural practices are needed to maximize yields, without concern for the representativeness of those practices for Malian conditions.

Second, calibration of the functions that reduce yields due to water stress requires data from controlled field experiments designed specifically for the purpose. Existing literature can, and should, be consulted as it is already fairly extensive for some crops grown in Mali (Goldsworthy and Fisher, 1984; Jackson, 1977; Frère and Popov, 1979; Doorenbos and Kassam, 1979). The local offices of ICRISAT and SAFGRAD should be consulted

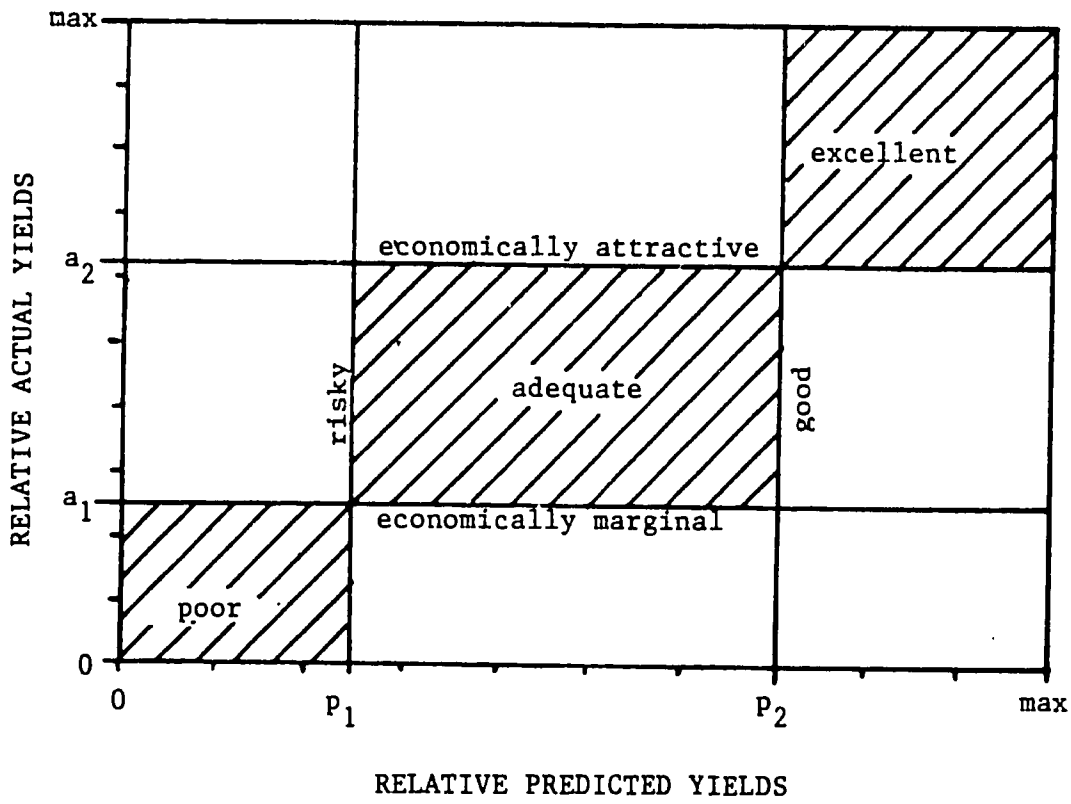

Figure 1. Conceptual scheme for utilizing predicted crop yields to classify a site according to its suitability for that crop. Values falling within the hatched areas are classified successfully. Class separation criteria for the X and Y axes may be very different.

frequently for news about research carried out elsewhere in the semi-arid tropics.

Third, one should verify the model against yield data from a wide range of site types and climatic zones. These data need not come from research stations, so long as yield can be expressed on a per unit area basis and the year and site can be identied. During this verification phase, one should resist the temptation to calibrate the model by trial-and-error. Calibration should always be based on an experimentally-derived understanding of crop phenology and physiology. Mismatches between actual and predicted yields discovered during verification can best be remedied by redefinition of those predicted yield values used to separate site suitability classes, i.e. the vertical lines in Figure 1.

In its present form, the model is most appropriate for short-cycle annual crops having harvestable products derived either from floral structures, e.g. cereals, pulses, groundnut, and cotton, or from the entire above-ground biomass, i.e. fodder crops. Tuber crops are specifically excluded, as are crops maturing in more than 365 days, e.g. banana. The model is inappropriate for an irrigated context, unless irrigation is used only as a supplement after the beginning of the rainy season; otherwise, the date of planting would always be 1 April. Multiple harvests per year are not considered.

The exclusion of tuber crops such as cassava, sweet potato (Ipomoea batatas), and yam (Dioscorea sp.) is unfortunate, but not disastrous to PIRT's zonage work. Most likely, reliable correlations already exist between yields of grain crops and those of tubers. The correlative approach is strongly recommended as long as the reference member of the correlated pair is sufficiently well understood that my model can reliably predict its yields. Alternatively, one could devise a separate model for tuber crops. I recently learned from Dr. M.V.K. Sivakumar of ICRISAT's Sahelian Center in Niamey, Niger that the International Institute for Tropical Agriculture (IITA) in Ibadan, Nigeria has already developed a climate-based model for tubers. Inquiries should be made directly to IITA.

Part II

Without further delay, let's examine a sample output from the computer program (Figure 2 a , b). First are listed assumptions about the climate at a given pluviometric station, then the assumptions about soil and crop characteristics, and next the calculated results for each year in the available rainfall record. In addition to estimated yield, the output reveals the number of false starts, the distribution of stress among phenological periods, and cumulative water balance terms for the cropping period.

Table 1 indicates how one can take a series of annual outputs and determine the value of yield at a chosen probability level, without resorting to complicated probability distributions. The method depicted is crude, but for small sample sizes and for the intended purpose, I recommend its use. The method's lack of statistical complexity and thus mysteriousness will render its limitations more obvious to the user, and thus will minimize misinterpretation of assigned probabilities. Users seeking a more sophisticated method for assigning probabilities should consult the computer program for the incomplete gamma distribution given in Appendix V of Sivakumar et al (1984). The gamma distribution is preferable to the normal or lognormal when the data set contains a significant number of zeroes.

The remainder of Part II discusses each component of the model. The order of the topics is not necessarily the same as that of their appearance in the computer program.

Climatic Inputs

Solar radiation at the top of the atmosphere (RTOP*) and the maximum potential number of sunshine hours (HSP) depend only on latitude, so mid-month values at 10 and 20 degrees latitude (Figure 3) were adapted from the Smithsonian Meteorological Tables (List, 1958), after correcting RTOP to reflect a solar constant of 2.0 cal/cm2/min. Midmonth values at the latitude of the given station are interpolated and then daily values (REX, HN) are interpolated; the user need only supply latitude to generate these values.

Table 1.5 in Annex B5 of TAMS (1983) supplies mean <u>monthly</u> hours of bright sunshine (HBSA) for 17 synoptic stations. For other stations, values should be read directly from a set of 12 monthly maps to be based on table 1.5. The input value, mean <u>daily</u> HBSA, is not the same as the value for the midmonth day so daily estimates (HBS) cannot easily be interpolated without inducing sizable biases. Consequently, each day within a month is assigned the same value.

Daily totals of radiation reaching crop level (RA) are lculated by the same equation adopted by Doorenbos and Pruitt 977) for their use with the Penman potential ET formula:

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*Wherever a symbolic name appears in capital letters, it refers to the variable name actually used in the computer program.

STATION NAME: MOPTI (SYNOPTIC STATION) DATE OF JOB: 04-NOV-85
LATITUDE: 14.52 DEG N
LENGTH OF NORMAL MOIST SEASON: 80 DAYS

DAILY VALUES AT MIDDLE OF MONTH
(WATER YEAR BEGINS 1 APR, NOT 1 JAN)

MONTH	TMEAN	RP	HBS	RA	ETP	BC	BO
1	32.80	578.5	7.84	522.5	9.03	437.9	234.5
2	31.20	584.6	8.07	528.6	9.10	449.0	240.5
3	28.40	581.1	7.48	500.3	7.10	452.7	241.8
4	27.20	580.5	6.94	481.8	6.23	451.3	241.9
5	27.50	578.4	7.87	519.9	6.30	444.4	238.2
6	28.40	559.3	8.61	538.8	7.65	428.8	228.5
7	26.30	518.2	8.63	510.1	7.13	400.2	211.2
8	22.90	469.1	6.94	414.7	5.68	369.3	192.3
9	22.50	433.9	8.00	420.1	6.84	349.7	179.9
10	26.90	451.0	8.57	453.0	8.61	356.8	184.6
11	28.80	500.2	8.48	491.1	8.81	386.5	202.8
12	31.60	550.6	8.37	525.9	9.07	416.0	220.9

SOIL TYPE ASSUMED: SILT LOAM
MAXIMUM ROOTING DEPTH: 1000. MM WATER HOLDING CAPACITY: 0.229 MM/MM
FRACTION OF SOIL MOISTURE THAT IS READILY AVAILABLE: 0.45

CROP: SORGHUM BICOLOR:110 DAYS
LAI: 3.0 CANOPY RADIATION EXTINCTION COEFF.: 0.5
YIELD FRACTION OF TOTAL BIOMASS: 0.25

DAYS REQUIRED FOR SEED GERMINATION: 7
DAYS (AFTER GERMINATION) TO REACH FULL SITE OCCUPANCY: 33
DAYS (AFTER GERMINATION) TO OVULE FERTILIZATION: 73
DAYS (AFTER GERMINATION) TO REACH FULL MATURITY: 110 (HARVEST)

CROP COEFFICIENTS FOR ET:
INITIAL = 0.40 MAXIMUM = 1.05 TERMINAL = 0.60

ASSUMED MAX PHOTOSYNTHESIS: 70. KG/HA(LEAF SURFACE)/HR
MIN AND MAX TEMPS (DEG C) OF OPTIMAL RANGE: 30. 32.
INTENSITY OF PAR NEEDED FOR SATURATION: 1.0 CAL/CM2/MIN
RESPIRATION COEFFICIENTS: GROWTH=0.280 MAINTENANCE=0.0108

ERATIO TRIGGERING CROP FAILURE (BEFORE DA2): 0.15
ERATIO THRESHOLDS FOR STRESS DAYS: 0.35 (TO DA1); 0.50 (FROM DA1 TO DA2)
FRACTIONAL REDUCTION OF YIELD FOR EACH STRESS DAY:
0.02 (TO DA1); 0.05 (FROM DA1 TO DA2); 0.01 (FROM DA2 TO HARVEST)

Figure 2a. Sample output of computer program.

```
YEAR:  1966     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED: 110 DAYS

CROP YIELD (KG/HA):
     4493. (NO MOISTURE CONSTRAINTS )
      449. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
     109        -99        -99        -99        -99        -99
DURATION OF GROWTH PERIOD(DAYS):
     117          0          0          0          0          0

SEASONAL RAINFALL TOTAL:  432.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  25.
ASSUMED ACTUAL SEASONAL ET:  407.

DAYS RETARDED DUE TO STRESS:   0
TOTAL YIELD REDUCTION DUE TO STRESS:  0.90
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.000  0.900  0.000
--------------------------------------------------------------------------

YEAR:  1967     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED: 110 DAYS

CROP YIELD (KG/HA):
     4513. (NO MOISTURE CONSTRAINTS )
     4513. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
     102        -99        -99        -99        -99        -99
DURATION OF GROWTH PERIOD(DAYS):
     117          0          0          0          0          0

SEASONAL RAINFALL TOTAL:  461.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  14.
ASSUMED ACTUAL SEASONAL ET:  447.

DAYS RETARDED DUE TO STRESS:   0
TOTAL YIELD REDUCTION DUE TO STRESS:  0.00
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.000  0.000  0.000
--------------------------------------------------------------------------

YEAR:  1968     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED: 110 DAYS

CROP YIELD (KG/HA):
     4527. (NO MOISTURE CONSTRAINTS )
     2490. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
      85        -99        -99        -99        -99        -99
DURATION OF GROWTH PERIOD(DAYS):
     118          0          0          0          0          0

SEASONAL RAINFALL TOTAL:  386.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  22.
ASSUMED ACTUAL SEASONAL ET:  364.

DAYS RETARDED DUE TO STRESS:   1
TOTAL YIELD REDUCTION DUE TO STRESS:  0.45
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.000  0.450  0.000
```

Figure 2b. Sample output of computer program, showing annual summaries for the station, soil, and crop assumed in Figure 2a.

Table 1. Recommended method for assessing probabilities of predicted actual yields.

Yield	Year[1]	Rank	Probability[2]
4513[3]	1967	1	.07
4320	1975	2	.14
4319	1969	3	.21
3454	1971	4	.29
2490	1968	5	.36
2280	1976	6	.43
1873	1970	7	.50
1403	1974	8	.57
449	1966	9	.64
0	1973	10	.71
0	1978	11	.78
0	1977	12	.86
0	1972	13	.93

[1]The year column is unnecessary to the procedure.

[2]Probability is calculated as:

$$p = m/n+1$$

where n=the number of years in the record (13), and m=the rank of the year. with the largest equal to 1.

[3]These values were taken from the "run" illustrated in Figure 2.

Note: Interpolating, the 75% probable yield is 0, the 67% yield is 257, the 60% yield is 994, etc.

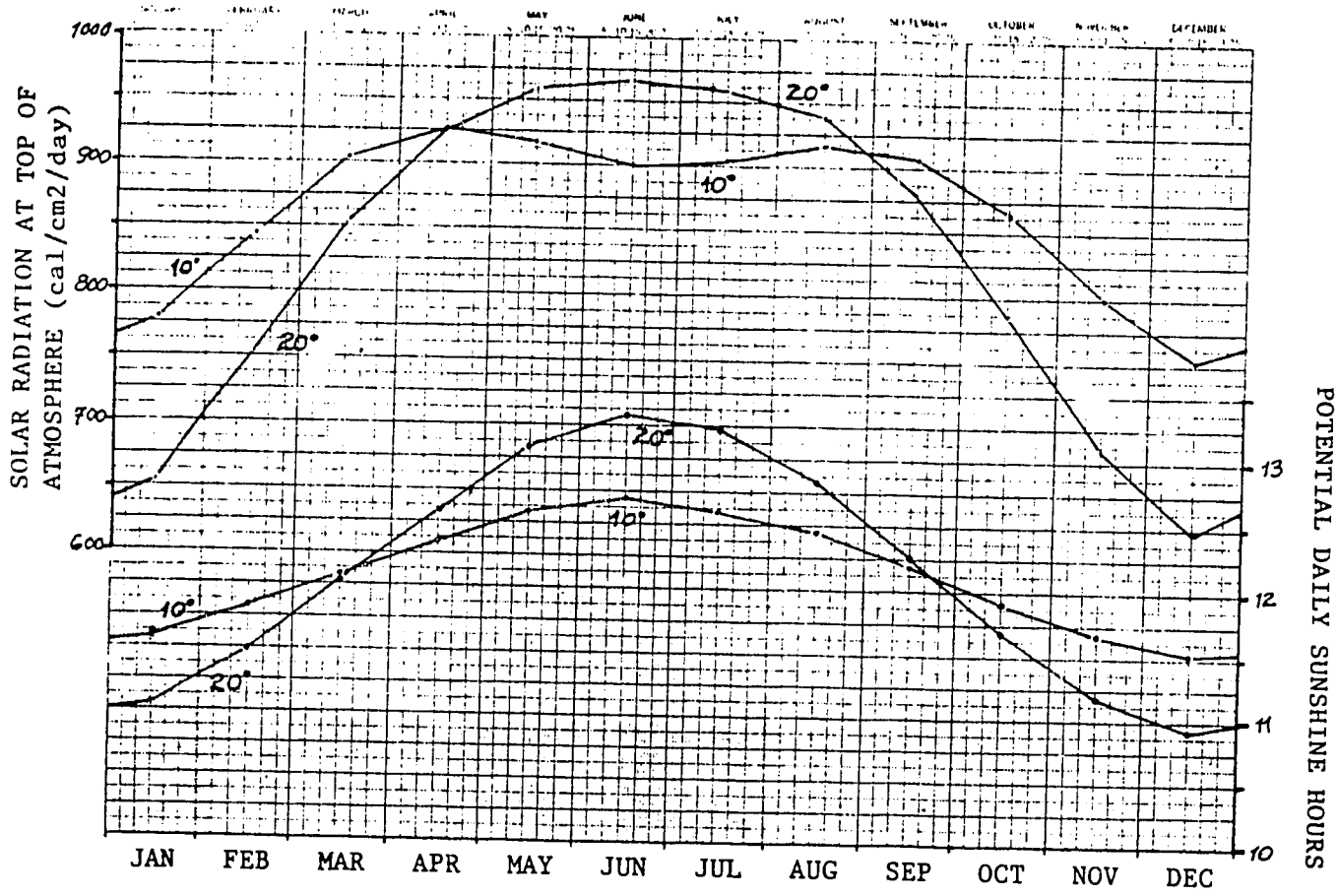

Figure 3. Solar radiation at the top of the atmosphere and potential daylight hours for 10 and 20° N latitudes. The points and straight segments indicate the values and interpolations used by the model.

$$RA = (.25 + .50\ HBS/HN)\ REX$$

The potential value for completely clear skies is:

$$RP = (.25 + .50\ (.75))\ REX$$

Radiation estimates are used only in the photosynthesis submodel, since potential ET is input directly. A concern about these equations is discussed in Appendix A.

Table 1.1 in Annex B5 of TAMS (1983) supplies monthly potential ET (PET) for synoptic stations. Values for other stations will be read directly off monthly maps to be based on Table 1.1. As with sunshine hours, the daily estimates inputted (ETP) cannot be interpolated, so the same value is applied across the month. No adjustments of ETP are made to reflect the occurance of rain.

In an analogous fashion, mean monthly temperatures (TEMP), derived from Table 1.2 in Annex B5 (TAMS, 1983), are input and daily values (TMEAN) assigned. 24-hour means are adequate since the only direct use of temperature in the model occurs in the calculation of 'dark' respiration losses, which operate both day <u>and</u> night.

[The temperature dependency of photosynthetic rates in Figure 3.1 of FAO (1978) assumes daytime temperatures. One can virtually ignore the relationships of Figure 3.1 since the range of computed mean <u>seasonal</u> temperature is relatively narrow. But, if desired, the program could be modified for an additional input of daily maximum temperatures (Tmax), which would permit calculation of daytime means (Td):

$$Td = TMEAN + .212\ (Tmax - TMEAN).$$

This equation was adopted from Milthorpe and Moorby (1979, p.223) and assumes a sinusoidal temperature cycle, with a minimum at dawn.]

Daily gross precipitation depths (PG) are input directly.

By the end of the climate set-up phase, RP, RA, TMEAN, ETP, and PG are established for 365 days, starting 1 April. Only PG changes from year to year. The two other variables established at this point (BC and BO) are discussed in the "Calculation of NPP" section.

Establishment of Sowing Dates

The model takes the date of sowing as the first day of the rainy season, defined as that day where rainfall in the preceeding ten days is greater than or equal to one-half of potential evaporation during the same period. When found, the date is noted, the topmost layer of soil is assumed fully wetted (deeper layers initially have no available moisture), and the calculation of daily water balances begins.

If a false start is later detected, a search for a second sowing date (or third, etc., up to six) resumes with the same criteria. The only difference from the first sowing is the retention of any soil moisture that may have reached the deeper layers during the previous period. If no sowing date is found, yield is of course zero.

Soil Characteristics

The soil is depicted as having a single texture for its entire depth. Texture merely implies a maximum volume fraction of available moisture, or water-holding capacity (WHC), plus a fraction of that WHC which is "easily" available (SMFRAC). Suggestions for the determination of WHC and SMFRAC are given in Appendix B.

Soil depth is equated with the ultimate depth of rooting for the specified crop.

Phenological Influences on the Water Balance

The model assumes the life cycle of a crop consists of four stages:

(1) Sowing through germination (SOWDAT to SOWDAT + GERM),

(2) Germination through to full site occupancy (DA = 1 to DA = DA1),

(3) Initiation of floral structures through fertilization of ovules (DA = DAC1 to DA = DAC2), and

(4) Fruit-filling and ripening (DA = DAC2 to DA = MAT), where DA represents developmental age and MAT, crop maturity.

If more stages are desired, minor programming revisions will be necessary; one can model fewer stages simply by equating DA1 and DA2 and/or DA2 and MAT, as appropriate.

Phenology affects the water balance in two ways: it controls the depth of soil exploited by roots and it defines the crop's evaporation rate when soil moisture is not limiting through the crop coefficient (KCROP). Figure 4 should help clarify the following discussion.

During the first stage, roots do not exist, but in anticipation of the radicle's initial growth requirements, adequate soil moisture must occur throughout an uppermost layer having thickness RDBASE (100 mm seems a good guess). The crop coefficient is then at its minimum, KBASE.

As the crop's developmental age increase, root depth (RD) and KCROP increase at a steady rate until their maximum values (RDMAX and KMAX) are reached at DA1. RD remains at RDMAX until crop maturity, but KCROP steadily decreases after DA2 due to occlusion of stomata, senescence of the stomatal response, leaf yellowing,

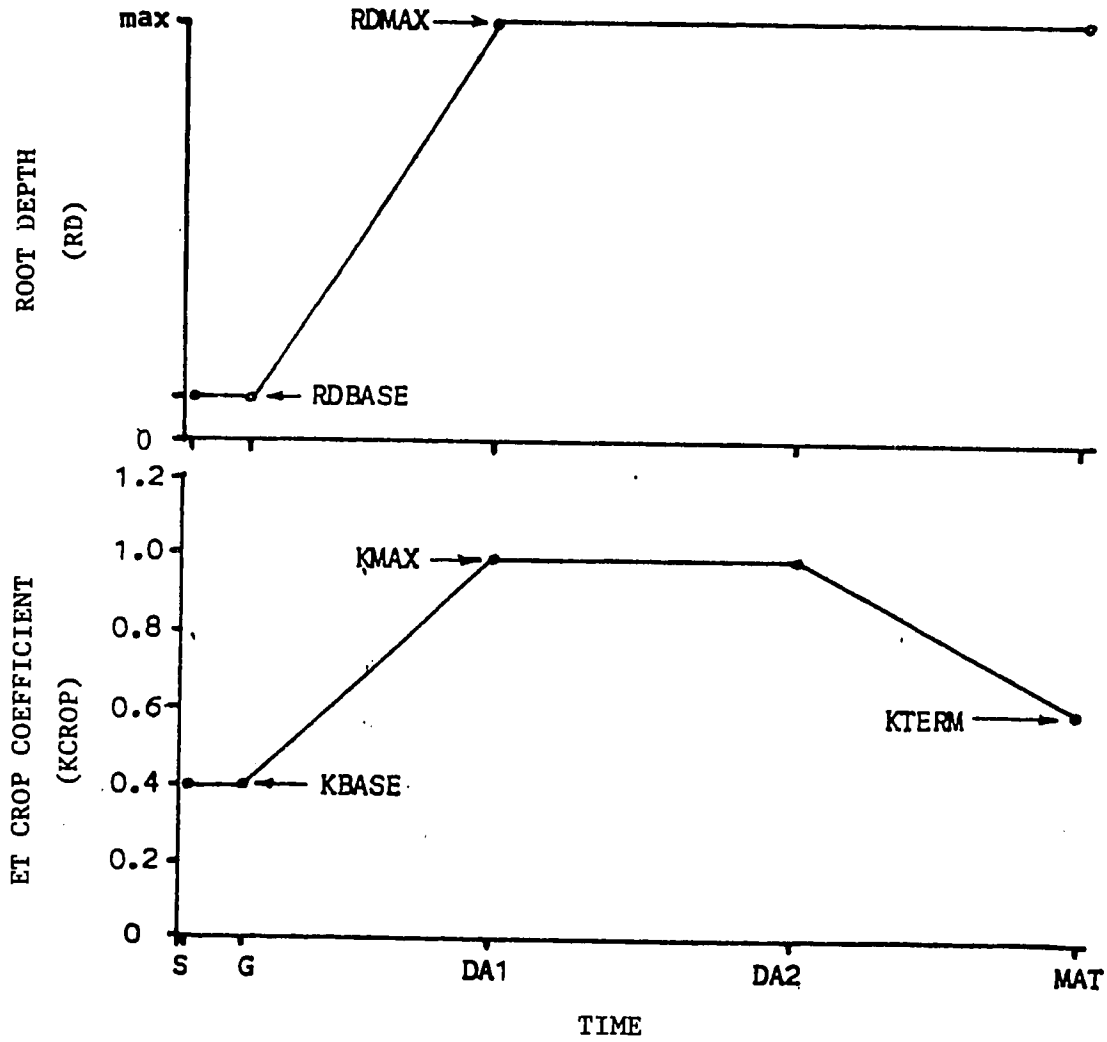

Figure 4. Model assumptions about the phenological relationships of root depth and crop coefficients for evapotranspiration.

and loss of foliage, until at harvest it has decreased to KTERM.

Following Doorenbos ant Pruitt (1977), the model assumes that maximum crop evapotranspiration in the absence of soil moisture constraints (ETC) is related very simply to the atmospheric evaporative demand (ETP): ETC = KCROP * ETP. Since the working definition of ETP assumes that the soil is fully occupied by a perennial short grass cover, KCROP need not remain below 1 for all crops. A tall crop such as maize is an inherently more efficient evaporating surface than short grass, due solely to enhanced turbulent mixing.

No attempt was made to relate KCROP to leaf area index (LAI) since many other factors are involved. Published KCROP estimates are determined empirically from direct observations, usually from lysimeter studies. Doorenbos and Pruitt (1977) provide suggested values for KBASE, KMAX, and KTERM, as well as DA1, DA2, and MAT for a limited number of species.

Calculation of Water Balance

A daily soil water balance is calculated from sowing to harvest, to detect stressful periods for crop development and thus permit calculation of yield reductions, and also to detect stress so severe that the crop fails to mature.

Daily rainfall (PG) is added directly to the soil, without reduction for canopy interception or surface runoff, before the day's assumed actual evapotranspiration (ETA) is calculated. FAO (1978) allowed only PG in excess of ETC to enter the soil which, in a high evaporation environment like Mali's, severely underestimates soil recharge. Daily rains less than 1 mm are ignored.

Actual ET is calculated in the following two ways:

(Before germination) ETA = ETC * ESM/ESMMAX

(After germination) ETA = ETC * min (1,ESM/(ESMMAX * (1-SMFRAC))) where ESM is the soil moisture of the effective soil depth (current root depth), ESMMAX is the maximum moisture storage for that depth, and the 'min' function takes the smaller of the two values separated by commas, thus preventing the expression from exceeding 1. The effect of the second equation is that ETA equals ETC as long as soil moisture does not drop below (1- SMFRAC) * ESMMAX. At lower values, reduction of ETA is a linear function of the moisture deficit. Appendix B gives further details. Unfortunately, these formulae fail to reflect that the evaporation ratio (ERATIO), i.e. ETA/ETC, depends in reality on the absolute value of ETC; low evaporative demand may be met by "dry" soil while a high demand may not.

The water balance detects stress as diagrammed in Figure 5 (comparison with Figure 4 may be helpful).

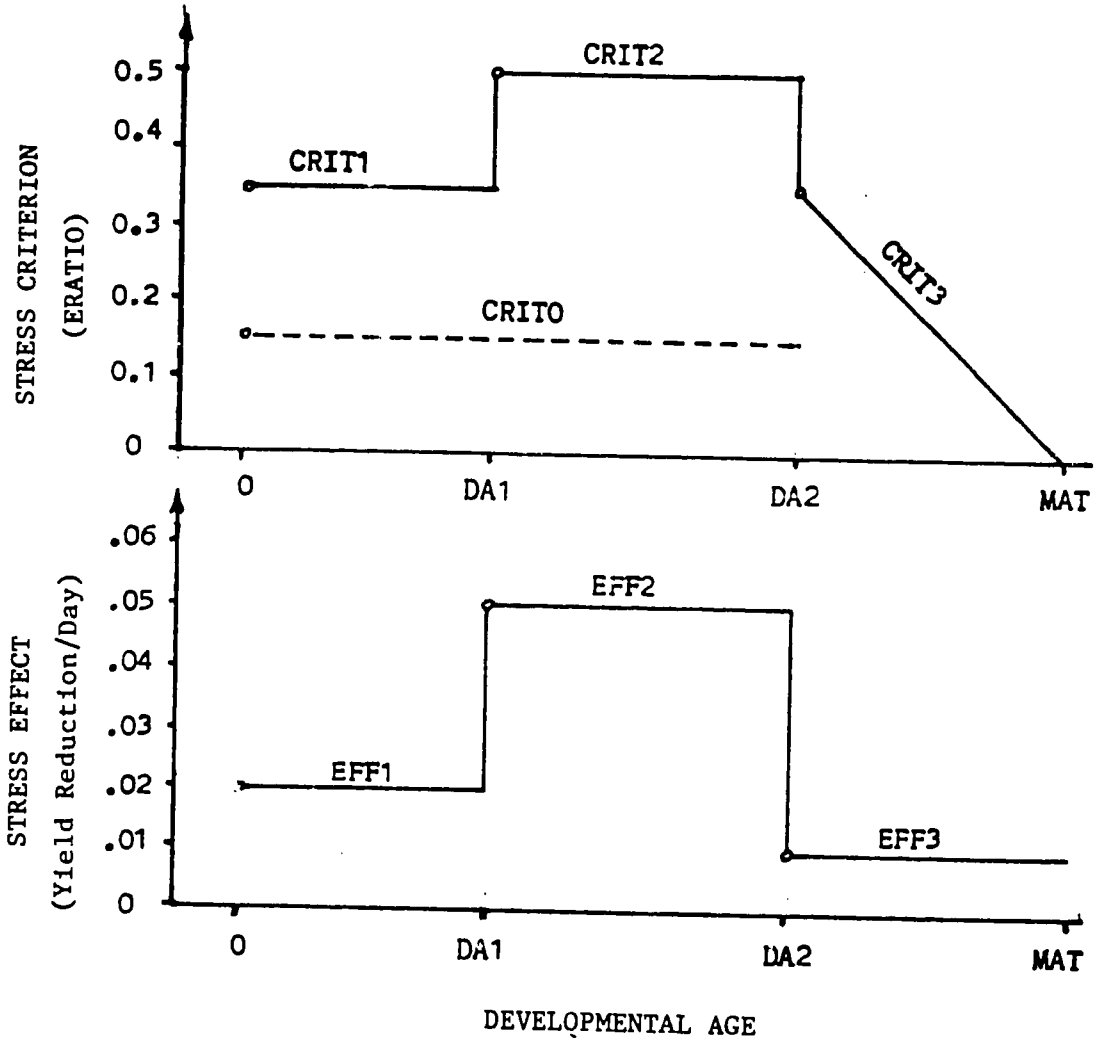

Figure 5. A hypothetical example of crop sensitivity to stress at each phenological stage. The values on the Y-axis are for illustration only. The upper graph shows stress detection threshholds, and the lower the yield reduction per stress day.

Four values of ERATIO can signal 'stress days'. The first, CRITO, has a dual purpose, depending on how far the crop has developed. If, before DA1, ERATIO drops below CRITO, a false start to the growing season is recorded and the model resumes looking for another sowing date; after DA1, a value below CRITO causes a crop failure for the entire year, without option of replanting.

The user must rely on informed judgement in specifying values for CRITO-CRIT3. The relative ranking implied in Figure 5 reflects my assumption that crops are more susceptible to moisture stress during the reproductive (flowering) stage than during purely vegetative stages, and also that the crop becomes almost immune to stress as grain-filling approaches completion.

For each stress day encountered, yield is reduced by the appropriate stress effect value (EFF). The full sensitivity of a crop to stress, therefore, involves the values chosen for both CRIT and EFF, a concept borrowed from Frère and Popov (1979). During early, purely vegetative growth, crop development may be temporarily halted by stress without necessarily having a substantial effect on future yield. Recognizing this, I permit (when DA < DA1) up to 10 days below CRIT1 before stress starts to invoke EFF1; consequently, a crop which is supposed to mature in 120 days may take as long as 130 days before DA = MAT.

With heavy or frequent rains occurring before root development is complete, soil moisture may percolate beyond the current root depth. Within a defined maximum, this deep moisture remains available for extraction as soon as roots penetrate to it. The model assumes that moisture passing beyond the current root zone proceeds only so far as will permit achievement of 'field capacity' by the layers involved. Field capacity here simply means that the available water holding capacity is full. Consequently, when root depth increases from RD1 to RD2, the new effective soil depth takes on (RD2-RD1) * WHC additional moisture, if available. This process is not the same as using all the surplus moisture in deeper layers to keep the current root depth fully wetted. Figure 6 attempts to clarify these relationship. The left-hand diagram indicates the conceptual basis for the incrementing of moisture contents as roots extend; soil moisture profiles are not, however, directly utilized in the model. The right-hand diagram indicates the relationships used in the actual computations, the value of each parameter being represented by its area.

Characterization of the Growth Period

As the next section will show, the stress-free productivity of the crop is calculated on the basis of conditions of the average day in the growth period, defined as the interval between sowing and harvest. One of the purposes of the water balance is to determine whether the growing period extends to crop maturity--if

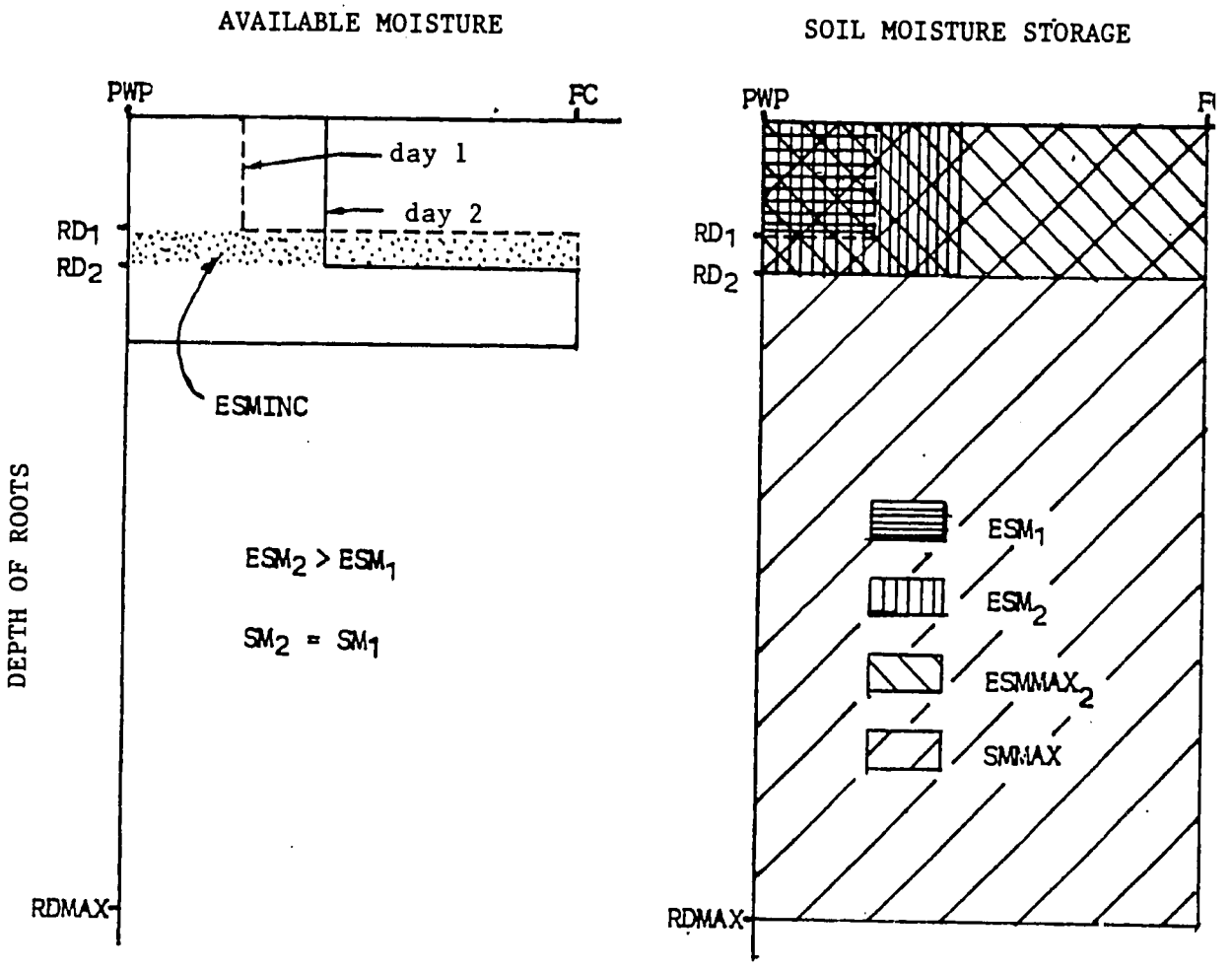

Figure 6. Example of soil moisture relationships for a pair of days during the root elongation period. See text for details.

it doesn't, yield equals zero. The development of root depth and of the ET coefficient (KCROP), necessary for water balance calculations, are independent of crop productivity, since the latter is estimated after the growing period is known and after percentage yield reductions due to stress are calculated.

Growing period means are calculated for temperature (to calculate respiration and, indirectly, to adjust photosynthesis), plus potential clear-sky insolation and assumed actual insolation (to calculate photosynthesis). These 3 parameters are not used to calculate evapotranspiration. For information alone, growing period totals of rainfall, evaporation, and deep seepage are calculated. Residual soil moisture in the root zone at harvest is also noted.

After the relatively big job of characterizing the growing period is complete, the computer program needs only 10 equations to calculate the crop yield.

Calculation of Yield

The assumption of a sigmoid crop growth curve, following FAO (1978), greatly simplifies the calculation of biomass production during the crop's lifetime. Figure 7 and 8 are taken from Figures 7.1 and 7.2 of FAO, modifying only the labels to match the conventions used in my report. Figure 7 expresses cumulative crop growth and Figure 8 the instantaneous rate of growth. With knowledge of the peak instantaneous rate, one can estimate the average rate throughout the crop's lifetime and thus the biomass accumulated at harvest (hatched rectangle in Figure 8):

$$BIOMAS = 0.5\ NPP * MAT$$

Where NPP is the maximum net primary productivity.

The sigmoid and bell-shaped curves of Figures 7 and 8 reflect the truisms that, in the early stages of crop development, the absolute level of dry matter production is low due to insufficient leaf area to capture the available radiation, and that, as maturity is approached, the photosynthetic tissues senesce, slowing growth. Furthermore, growth of fruit often comes at the expense of starches formed earlier and stored elsewhere in the plant.

The ratio between yield of the economically-useful product and the total aboveground biomass is called the harvest index (HINDEX); the user must specify its value. Potential yield (YLDPOT) is thus:

$$YLDPOT = BIOMAS * HINDEX$$

Potential yield in the absence of moisture constraints is then reduced by the accumulation of stress units through the growing period (CUMRED):

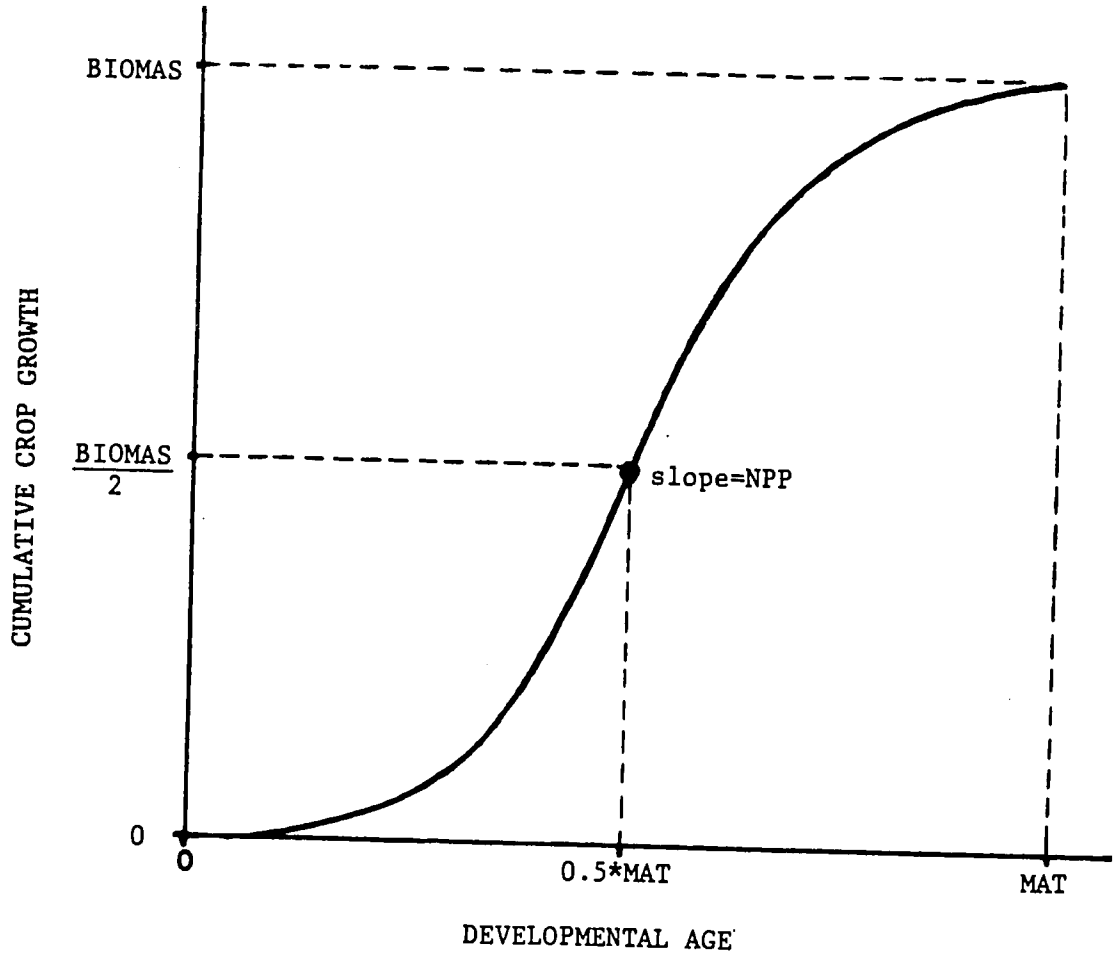

Figure 7. Idealized cumulative growth curve for all crops modelled.

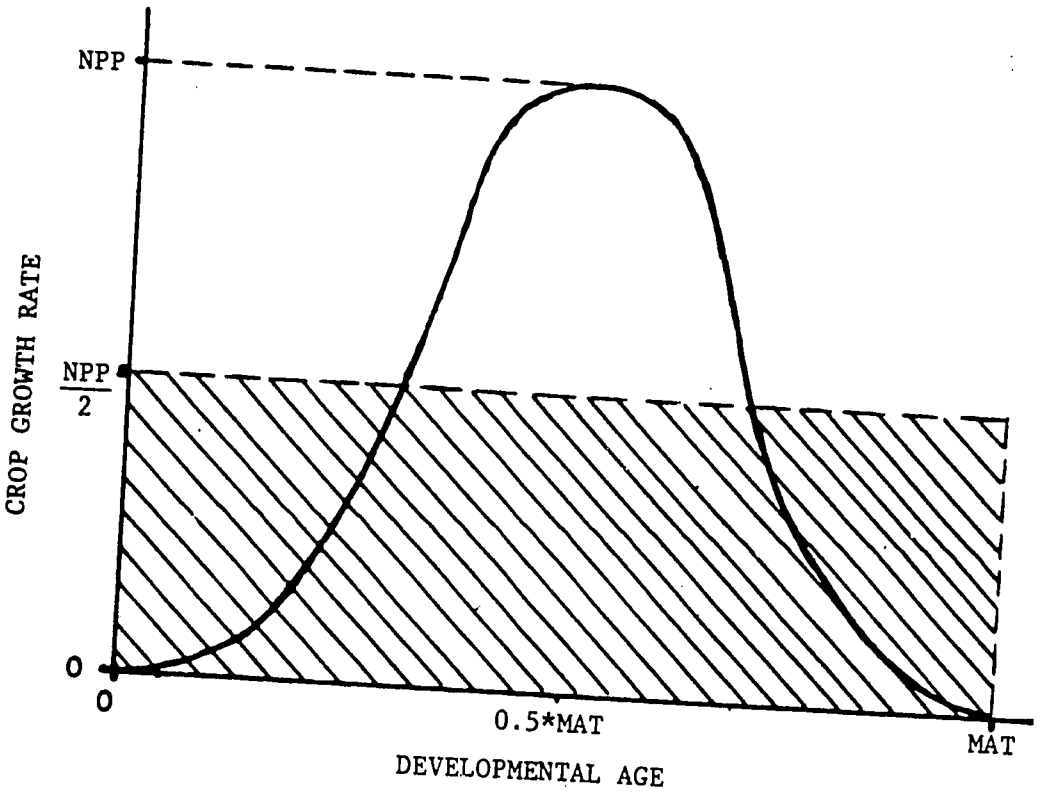

Figure 8. Idealized instantaneous growth rate curve for all crops modelled.

YLDACT = YLDPOT * (1-min (1,CUMRED))

YLDACT is the model's theoretical estimate of maximum yield achievable under the given year's rainfall regime.

Calculation of NPP

Conceptualization of yield as a function of NPP is straightforward and does not disguise its oversimplifications. The same cannot be said for the calculation of NPP, which is fraught with difficulties arising primarily from its dependence on empirical relationships either which are not documented or which may be inappropriate for conditions or crops grown in Mali.

By definition, NPP equals gross primary productivity (GPP) minus respiration losses--whether NPP is the maximum crop value as used here, or some other daily value. GPP is a function of temperature and radiation capture, while respiration is taken to be a function of temperature alone.

Following FAO (1978), GPP is based on a maximum photosynthetic rate per unit leaf area (PSM), having units of kg/ha/hr (see Appendix C), and a leaf area index (LAI) of 5, intercepting 95 % of incident radiation. The photosynthetic machinery of each leaf is saturated at a certain level of photosynthetically-active radiation (PAR), which, being a constant percentage of total solar radiation (50 %), is an unnecessary variable. Leaf photosynthesis (P1) equals PSM only at or above saturation radiation levels.

Any calculation of hourly photosynthesis for the entire crop canopy is complicated. First, due to the inherent variation of radiation across the day, fully-exposed leaves are unsaturated near dawn and dusk and probably saturated at midday. Second, a canopy with LAI = 5 will not have 5*P1 total photosynthesis, since lower leaves are shaded by upper leaves. Third, the typical growing period day may not be perfectly clear, and the relative performance of upper and lower leaves depends strongly on the radiation regime, in particular, whether upper leaves are saturated, and the proportion of diffuse to direct beam radiation. Thus, GPP is far from being a linear function of radiation.

De Wit (as presented in FAO (1978)) has fortunately dealt with these computational difficulties already--how successfully I cannot be certain. Table 7.2 in FAO presents GPP values for totally clear days (BC) versus totally overcast days (BO), both of which assume PSM = 20 kg/ha/hr and LAI = 5. P1 thus need not be known.

For days intermediate in cloudiness:

$$GPP = F * BO + (1 - F) * BC$$

where F = (RP - RA)/(.8 * RP). When RA = RP, F = 0, and when RA = 0.2*RP (assumed to indicate complete overcast), F = 1. [Appendix A discusses a problem with cloudiness estimation.] Monthly values of BC and BO for 10 and 20 degrees latitude are listed in my Table 2 and the interpolated values implied by the computer program are graphed in Figure 9.

For crops with PSM other than 20, "it can be shown" (FAO, 1978) that the following corrected GPP equations are valid:

$$Y = (PSM - 20)/20$$

(For PSM > 20) $$GPP = F(1+.2Y)BO + (1-F)(1+.5Y)BC$$

(For PSM < 20) $$GPP = F(1+2.5Y)BO + (1-F)(1+Y)BC$$

The justification of these corrections was not shown.

FAO (1978) distinguishes among five groups of crops as regards their photosynthetic responses, and provides for each group a range of PSM values plus the temperature range within which the PSM values hold, without suggesting the relative ranking of crops within the PSM range (see Tables 3.1-3.5). Figure 3.1 shows the average relationship between PSM within each group and mean daytime temperature. As these relationships could not be expressed as equations, I did not attempt to incorporate them directly into the model. A single value of PSM is adequate as long as the mean growing period temperature falls within the optimum range. If the computer program detects a temperature that is too cool or too warm, it prompts the user to provide a new value (PSCOR), manually derived from FAO's Figure 3.1, before continuing to calculate Y and then GPP. The user initially sets PSCOR equal to PSM.

For crops with LAI less than 5 when grown at optimal densities, FAO (1978) provides a curve for adjusting calculated GPP which is derived from DeWit. Again, neither an explanation nor equation for the curve was given. The nearest approximation I could derive uses a Menten-Michaelis type equation, as commonly used in chemistry:

$$ADJ = 1.80 * LAI/(4.0 + LAI)$$

A second type of equation gives a poorer fit, but has a better theoretical foundation and is often used in crop modelling:

$$ADJ = 1 - \exp(-KANGLE * LAI)$$

where 'exp' is the exponential function. This equation is an application of Beer's Law for light extinction by an absorbing medium, and KANGLE is the extinction coefficient specific to each crop, incorporating effects of leaf angle, leaf azimuth, and the three-dimensional distribution of foliage. The amount of light

Table 2. GPP, in kg/ha/day, for closed crop canopy on very clear (BC) and wholly overcast (BO) days for reference crop with maximum leaf photosynthesis of 20 kg/ha/hr. Adapted from Table 7.2 of FAO (1978).

Month (mid-month value)	Lat 10 deg N		Lat 20 deg N	
	BC	BO	BC	BO
Jan	376	197	334	170
Feb	401	212	371	193
Mar	422	225	407	215
Apr	437	234	439	235
May	440	236	460	246
Jun	440	235	468	250
Jul	440	236	465	249
Aug	439	235	451	242
Sep	431	230	425	226
Oct	411	218	387	203
Nov	385	203	348	178
Dec	370	193	325	164

Latitudinal interpolation for the station of interest is linear between the 10 and 20 degrees values above. Since the resulting annual curve is quite smooth, interpolation for daily values can also be linear (see Figure9).

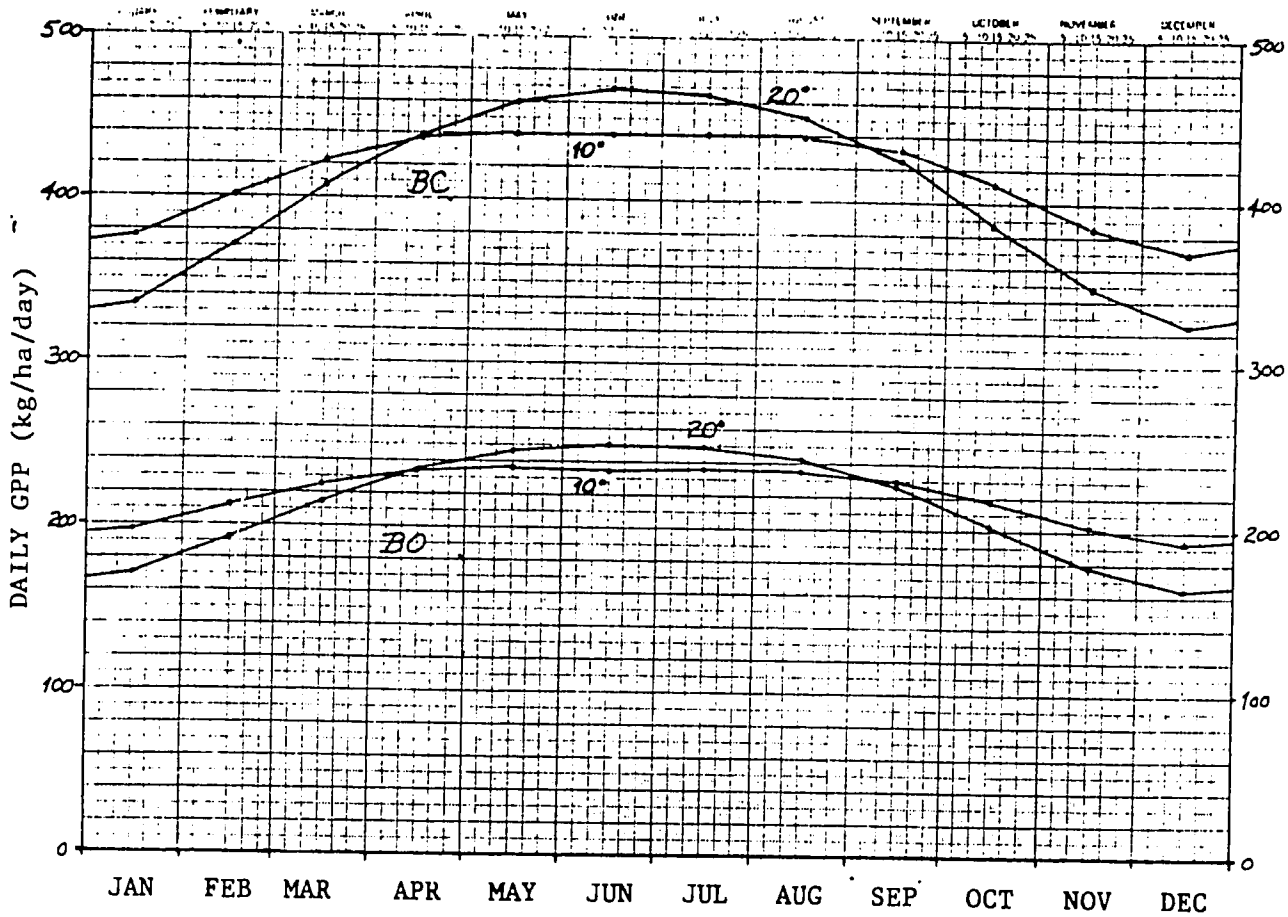

Figure 9. Potential daily crop growth rates at 10 and 20° N latitudes, assuming maximum leaf photosynthesis of 20 kg/ha/hr and leaf area index of 5, for days with skies perfectly clear (BC) or totally overcast(BO).

captured by such different crops as maize, cabbage, and onions would be very different even if LAI were the same; through KANGLE, one can quantify this effect of canopy architecture. Figure 10 compares the curves just discussed. Until better estimates of KANGLE can be obtained* for Malian crops and conditions, a value of 0.5 should be adopted, as it best approximates FAO's Figure 7.3.

The model estimates respiration losses for the day midway through the growth cycle, at which time respiration must maintain existing biomass, which is half of that at harvest, as well as support the building of the current growth increment:

respiration = KMAIN (0.5*BIOMAS) + KGROW*GPP

where KMAIN and KGROW are user-supplied coefficients for maintainance and growth respiration, respectively.
FAO (1978) suggests that KGROW = 0.28 at all temperatures and for all crops, that KMAIN = 0.0108 for non-legume, and 0.0283 for legume, crops at 30 degrees C, and that at other temperatures:

KMAIN = KMAIN30 (.044 + .0019T + .0010T2)

The authors base these suggestions on a single research paper (McCree, 1974) which reports on experiments with white clover (a temperate, leguminous forage crop) and grain sorghum. Having not seen the paper, I must view with some scepticism the appropriateness of these assumptions for Malian crops in general.

The model implicitly calculates respiration without prior knowledge of BIOMAS. Recall that:

BIOMAS = 0.5 * NPP * MAT, and

NPP = GPP - respiration

Substituting the first equation in the equation for respiration gives:

respiration = KMAIN (.25 * NPP * MAT) + KGROW * GPP

Substituting the last into the second equation gives:

NPP = GPP - KMAIN (.25 * NPP * MAT) - KGROW * GPP

which, after simplification, is the equation used in the program:

NPP = (1 - KGROW) GPP/(1+(.25 * KMAIN * MAT))

To refresh the reader's memory, calculation of yield is accomplished with just three additional equations:

BIOMAS = 0.5 * NPP * MAT

YLDPOT = BIOMAS * HINDEX

YLDACT = YLDPOT * (1-min (1, CUMRED))

Yield has units of kilograms of dry organic matter per hectare per harvest.

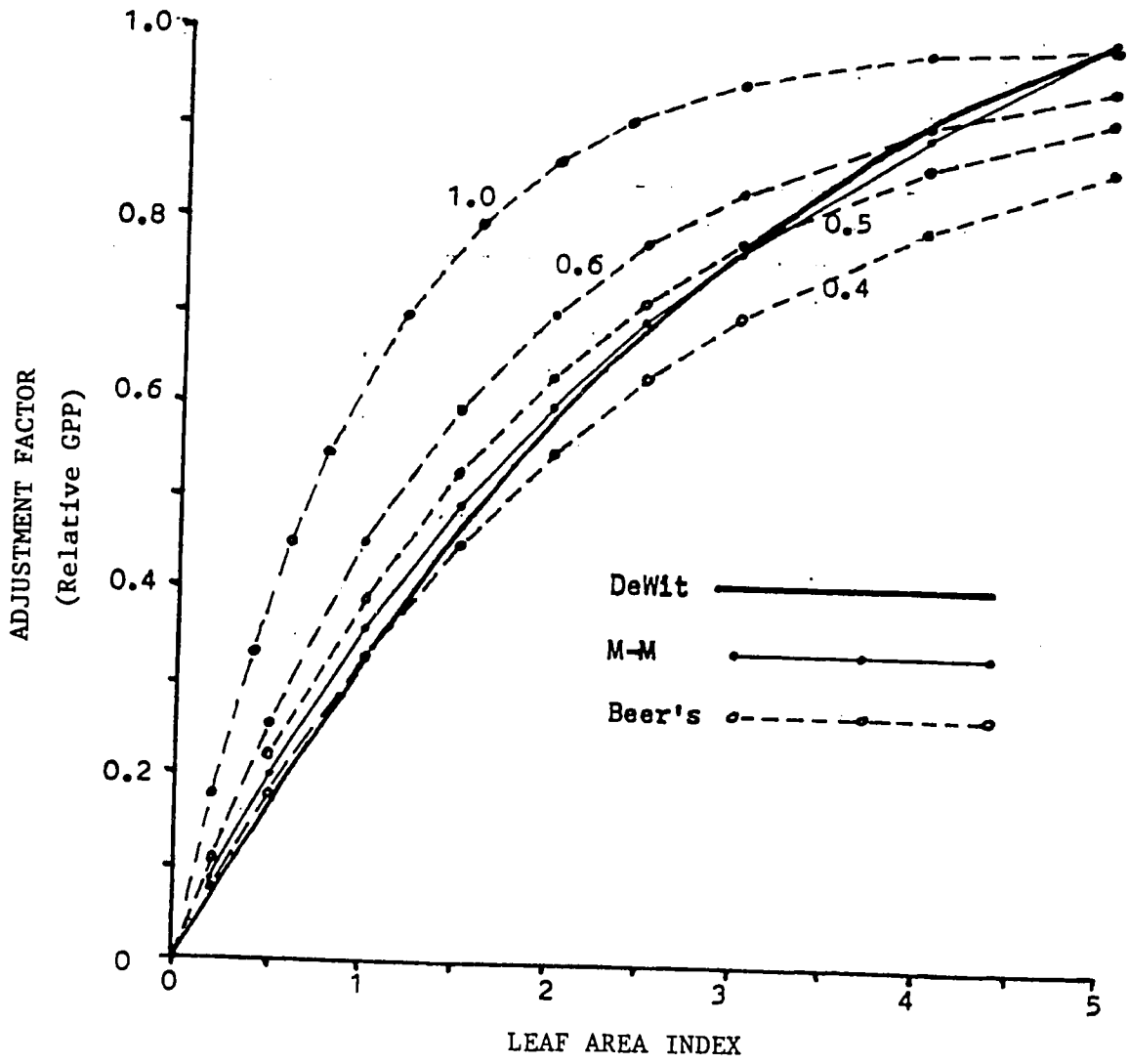

Figure 10. Adjustment to gross primary productivity for crop canopies that do not fully capture available radiation. Darkest curve, with no plotting points, is copied from Fig. 7.3 of FAO (78). The numbers on the family of dashed curves are extinction coefficients.

REFERENCES

[Entries marked by an asterisk (*) are available in the PIRT documentation center. When appropriate, PIRT accession numbers are also noted.]

*Cochemé, J. 1966. FAO/UNESCO/WHO agroclimatology survey of a semi-arid area in West Africa south of the Sahara. Pp.235-248 in Agroclimatological Methods. UNESCO symposium on methods in agroclimatology. University of Reading, 392p.

*Cochemé, J. and P. Franquin. 1974. An agroclimatology survey of a semi-arid area in Africa south of the Sahara. Technical Note No. 86, World Meteorological Organization, Geneva, 136p. [PIRT #120, 160].

*Doorenbos, J. and W.O. Pruitt. 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper No. 24, Food and Agriculture Organization of the United Nations, Rome, 144p. [PIRT#233].

Doorenbos, J. and A.H. Kassam (eds.). 1979. Yield responses to water. Irrigation and Drainage Paper No. 33, Food and Agriculture Organization of the United Nations, Rome, 193p. (N.V.)

*FAO. 1978. Report on the agro-ecological zones project. Vol. 1: Methodology and results for Africa. World Soil Resources Report No. 48, Food and Agriculture Organization of the United Nations, Rome, 158p. [PIRT#1247].

*Frère, M. and G.F. Popov. 1979. Agrometeorological crop monitoring and forecasting. Plant Production and Protection Paper No. 17, Food and Agriculture Organization of the United Nations, Rome [PIRT#?]

Goldsworthy, P.R. and N.M. Fisher (eds.) 1984. The physiology of tropical field crops, (publisher?)

*Hillel, D. 1971. Soil and water: physical principles and processes. Academic Press, London, 288p. [PIRT#100].

Jackson, I.J. 1977. Climate, water, and agriculture in the tropics. Longman, London.

List, R.J. 1958. Smithsonian meteorological tables. Smithsonian Misc. Collection, vol.114 (also listed as Smithsonian Institute Publication 4014), Washington, D.C., 527p.

McCree, K.J. 1974. Equations for the rate of dark respiration of white clover and grain sorghum, as functions of dry weight, photosynthetic rate, and temperature. Crop Science 14:509-514.

Milthorpe, F.L. and J. Moorby. 1979. An introduction to crop physiology. Cambridge University, Cambridge.

*Penman, H.L. 1948. Natural evaporation from open water, bare soil, and grass. Proceedings of the Royal Society of London (Series A), vol. 193, pp.120-145.

*Rawls, W.J. D.L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil water properties. Transactions of the American Society of Agricultural Engineers, vol. 25, no. 5, pp.1316-1320, 1328.

*Sivakumar, M.V.K., M. Konate, and S.M. Virmani. 1984. Agroclimatology of West Africa: Mali. Information Bulletin No. 19. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 294p. (A French edition has been printed)

Appendix A: Cloudiness Estimates and the Radiation Formula

A widely-used empirical formula for estimating solar radiation after its depletion by the atmosphere is:

$$R = (.25 + .50\ n/N)\ Ro$$

where the ratio n/N is a measure of the atmosphere's opacity, due to the presence of either clouds, dust, or haze. On the clearest possible day, n/N will never equal 1, even though the ratio is often described as that between actual and possible sunshine hours. Actually, N is the number of hours between sunrise and sunset, as calculated by an astronomical formula; n, on the other hand, is the observed number of hours of bright sunshine, as measured by any of several intensity-sensitive devices. The one most commonly used around the world, and the one used at Mali's synoptic meteorological stations, is the Campbell-Stokes sunshine recorder. Its glass sphere focuses the sun's beams on a strip of paper, burning the paper whenever the intensity is above approximately 0.34 cal/cm2/min. The scaled length of the burned strip is 'n'. An idealized curve of insolation on a clear day illustrates n and N (Fig.A.1).

No problem will arise as long as the formula is applied in the intended way, with N taken from tables and n taken from actual observations (burned strips). But what if we need to estimate the maximum potential insolation for a clear day? We can't simply set n/N equal to 1. What value of n, or what value for the ratio, is appropriate?

This quandary arises in the use of F, BC, and BO to estimate GPP. Since F is based on a comparison of clear sky insolation to estimated actual insolation, F is biased if clear sky insolation is biased. For example, given Ro = 900, N = 12.0, and n = 6.5, if the clear sky ratio of n/N equals 1, then F = .382; if clear sky n/N equals 0.75, then F = 0.208. Given BC = 448 and BO = 238 for June, the first F yields a GPP of 368, the second F yields a GPP of 404, a 9.9 % difference. Or, looked at another way, on a perfectly clear day in June, GPP should equal 448, but if the maximum observable ratio of n/N for such a day is in fact only 0.75, and n/N = 1 has been assumed for the potential case, then GPP for that clear day can only reach 404, or 90 % of the value intended.

The best solution to this quandary is to adopt whatever clear sky convention De wit used in developing his BC and BO values. Until his papers can be consulted, I've programmed the model to assume n/N = .75 for the potential case, a value suggested by Figure A.1.

This ratio is close to a maximum, so the yield estimates will still have a negative bias.

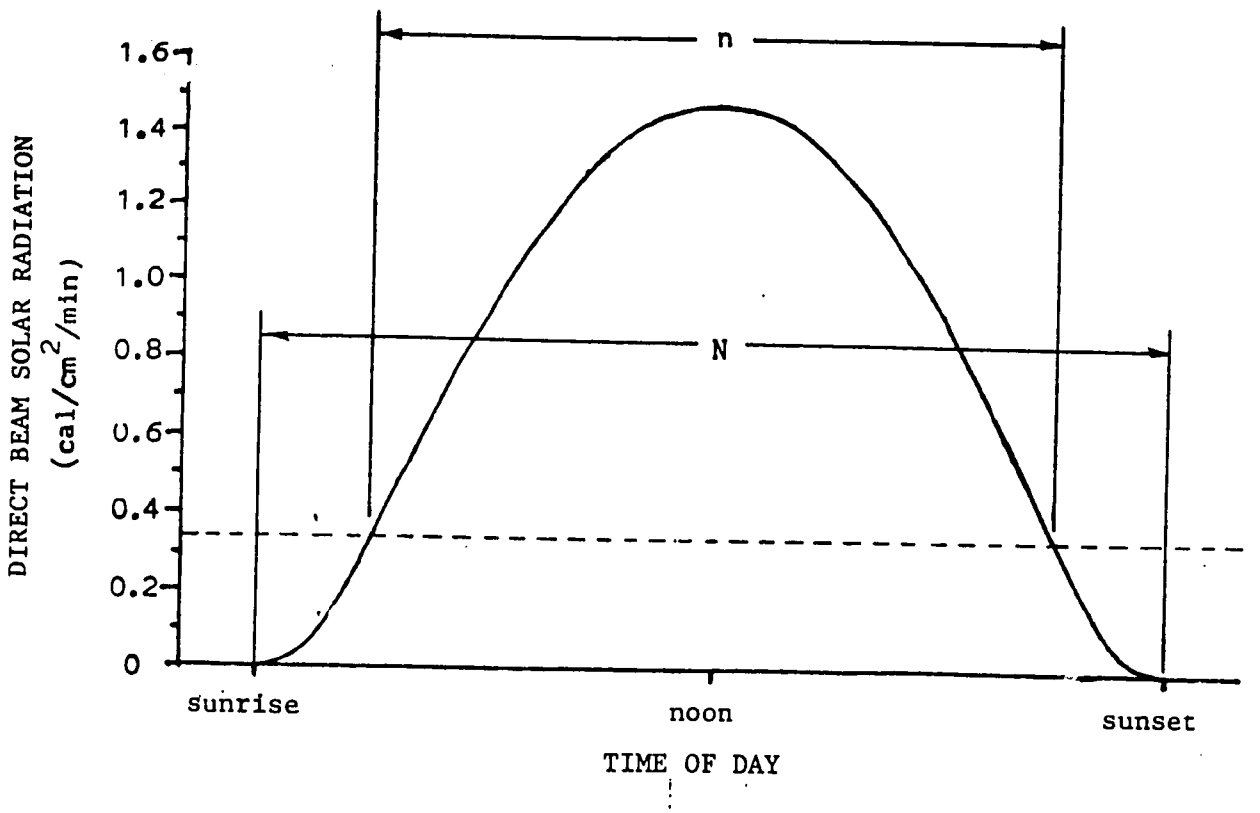

Figure A.1. Hypothetical distribution of radiation on a horizontal surface for one day, illustrating the definitions of possible daylight hours (N) and hours of bright sunshine (n).

Appendix B: Soil Moisture Availability

The modern concept of soil water availability to plants takes into account the energy with which the soil holds its moisture, unsaturated hydraulic conductivity, root distribution, physiological aptitude of the plants, and atmospheric evaporative demand. Availability is not a simple function of soil moisture content for, at the same moisture content, one crop may be able to maintain a near maximum transpiration rate while another may wilt. For a thorough discussion of this phenomenon, the interested reader is directed to the small text by Hillel (1971), especially sections 7E-G, 10B-C, and 3H. But the pursuit of realism necessarily involves increasing model complexity and requires many input variables that are simply not available. One must therefore compromise.

The ration between ETA and ETC (ERATIO) is given as a function of relative soil moisture in Figure B1. Two curves are used, implying the increased efficiency of transpiration over evaporation from the soil surface. The two curves express the relationships implied by the computer program. To give quantitative definition to these curves, the user must specify WHC--since ESMMAX = RD * WHC--and SMFRAC. To model the specific soil for which crop yield data are available or for which predictions are sought, one must have an objective technique for estimating WHC and SMFRAC. On the assumption that a soil can be characterized by the texture of its dominant horizon, the following method is suggested.

From a moisture release curve for each soil, as illustrated in Figure B.2, determine the moisture contents at tensions of 102 cm H20 ('field capacity') and 15300 cm H20 ('permanent wilting point') where 1020 cm H20 is equivalent to one bar. WHC is the difference between field capacity and wilting point moisture contents. SMFRAC is the difference between field capacity and the water content at which the slope of the moisture release curve is -0.002/cm H20, divided by WHC. To accomplish this, one clearly needs a moisture release equation for each soil texture.

A compilation of moisture retention data for 5350 soil horizons from all sections of the United States, including semi-arid and arid zone regions, has been reported by Rawls et al (1982). Moisture content (M) and matric tension (T) are related as follows:

$$M = (a/T)^b * (c-d) + d \qquad (1)$$

$$T = a((c-d)/(M-d))^{1/b} \qquad (2)$$

where a, b, c, and d are statistically-derived coefficients with the following values for each soil (adapted from Table 2 in Rawls et al, 1982):

Texture	a	b	c	d
Sand	7.26	.592	.437	.020
Loamy sand	8.69	.474	.437	.035
Sandy loam	14.66	.322	.453	.041
Loam	11.15	.220	.463	.027
Silt loam	20.76	.221	.501	.015
Sandy clay loam	28.08	.250	.398	.068
Clay loam	25.89	.194	.464	.075
Silty clay loam	32.56	.151	.471	.040
Sandy clay	29.17	.168	.430	.109
Silty clay	34.19	.127	.479	.056
Clay	37.30	.131	.475	.090

The tension at which the slope (or first derivative) equals -0.002 is defined by:

$$T_s = 500*b*a^b/(c-d)^{b+1} \qquad (3)$$

Moisture contents corresponding to tensions of ~~203~~ 102, T_s, and 15300 can be calculated from equation 1. Results for three textures are given below:

Texture	T_s	Moisture content @ 102	T_s	15300	WHC	SMFRAC
Sand	1442	.107	.038	.024	.083	.83
Silt loam	521	.357	.253	.128	.229	.45
Clay	310	.427	.382	.265	.162	.28

SMFRAC estimates are compatible with the fact that coarse soils readily release their stored moisture and that fine-textured soils hold on to theirs tightly. They also correspond to the common generalization that coarse, medium, and fine-textured soils have values for SMFRAC of .75, .50, and .25, respectively.

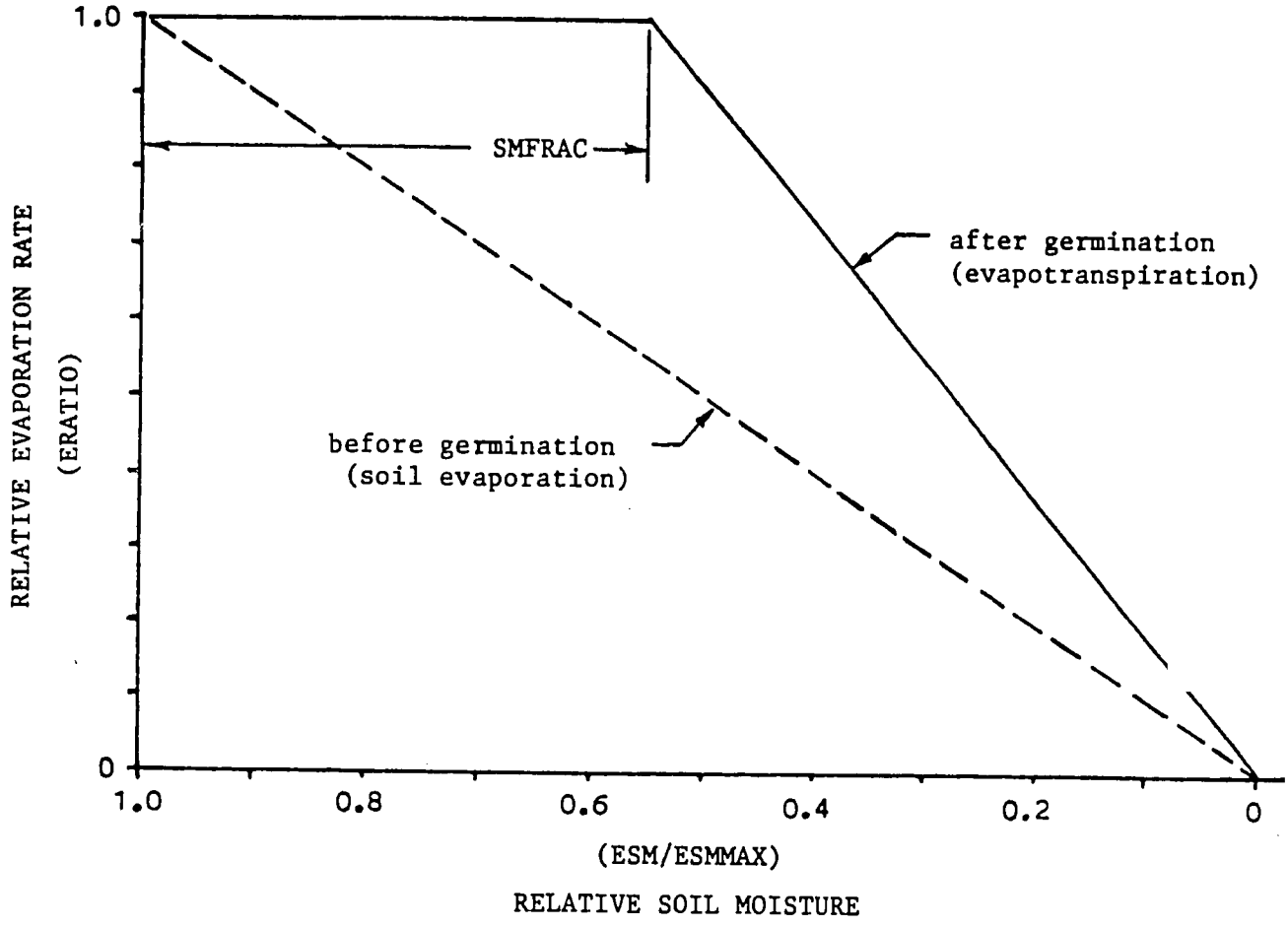

Figure B.1. Relative evaporation rates as functions of soil moisture status. The model used the dotted line before germination and the solid line at all times after germination. If SMFRAC=0, the two lines are identical.

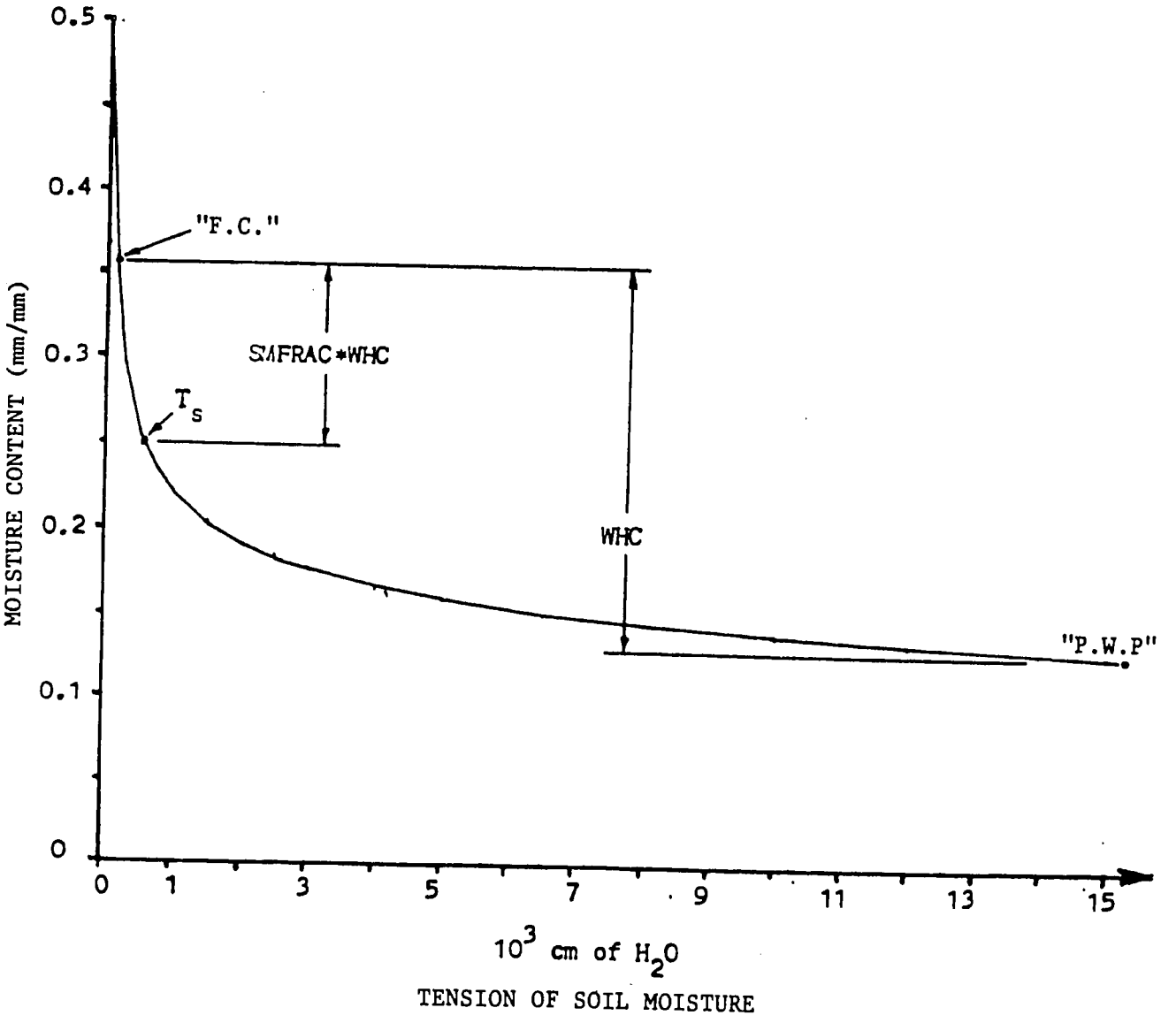

Figure B.2. Hypothetical moisture release curve for soil of medium texture, illustrating the determination of water holding capacity and its fraction that is readily available.

Appendix C: Units for Photosynthetic Rates

The units used in FAO (1978) can be confusing, as with Figure 3.2 in which the y-axis supports two scales. These scales give different values, even though mg/dm2 = kg/ha. Perhaps the explanation lies in the molecular weights assumed: mg/dm2 usually implies CO2 while, in the FAO usage, kg/ha implies CH2O (carbohydrate). I can find no explanation for this discrepancy, so suggest that the mg/dm2 scale on Figure 3.2 be ignored and that the PSM values given in Tables 3.1-3.5 also be ignored. PSM in kg/ha/hr can be read directly from Figure 3.2.

The use of hectares to represent leaf area can also be confusing, especially when not explicitly stated. However, in FAO (1978), kg/ha/hour always implies a leaf area basis, while kg/ha/day implies a land area basis.

PART III

The computer program, written in the Fortran IV language, has been designed specifically for the computer available to me for this work--and the one on which future applications are expected to take place. The computer is a PDP 11, manufactured by Digital Equipment Corporation, and is presently configured with a teletype terminal and two drives for diskettes ("floppy disks"), and uses an operating system called RT-11SJ. The input/output devices are very slow, and the operating system is not particularly versatile for file management and editting. However, the computer system is in the process of being greatly improved. Three high-speed hard disk drives, a magnetic tape unit, and a line printer are in place. As soon as the operating system software arrives, the computing system will be very efficient. The computer facility is officially shared by the Division d'Agrometeorologie of the Direction National de Meteorologie, and the Direction National de l'Hydraulique et l'Energie. It is housed in the control tower of the ASECNA block at the Bamako/Senou airport. AGRHYMET is financing the upgrading of the facility.

I have been fortunate to have the amiable assistance of Cheik Oumar Coulibaly and Kalilou Traore of the Division d'Agrometeorologie throughout my work. M Coulibaly not only helped me learn the computer's operating system, but always remained with me at the facility and thereby proved invaluable in remedying hardware problems promptly and efficiently. M Traore served as the formal liaison between PIRT and Agrometeorologie:

he freely provided me with rainfall data on diskettes, other supplies, and friendly general counsel. To both these men, I am indebted. My thanks also go to M Oster of L'Hydraulique et l'Energie, who cooperated in establishing a schedule of use that was much to my advantage.

To obtain diskettes containing daily rainfall data from all the synoptic and pluviometric stations in Mali's meteorological network, inquiries should be made directly to M M. Konate, Chief of the Division d'Agrometeorology. I am providing PIRT with a diskette containing, as examples, one file of each of the two data series that appear to be most useful. The "P" series consists of one long file representing many stations and occupying an entire diskette. Each file has the name PMALXX.DAT, where XX is a sequence number, going from 01 to 12 or more. The P series contains the record from 1966 to 1978. The "M" series consists of several files per diskette, each file having the name MXXX.DAT, where XXX is a station identification number; each file has data for only one station and pertains to an earlier period, e.g. 1950-1972. Because of the differences between these two series, different versions of the program were necessary. YIELDP.FOR, RENDP.FOR, and VITEP.FOR use the P series, while YIELDM.FOR and RENDM.FOR use the M series. YIELD is the English version; REND is the French.

My suggestion for future work with the model is that PIRT, in anticipation of the imminent improvement in the computer facility, request from AGRHYMET, through the Division d'Agrometeorologie, a magnetic tape containing the pluviometric data in a format most efficient for use with the model. Data from the tape can be stored in workable portions on the high-speed hard disks, thus allowing for highly productive sessions with the computer.

Alternatively, PIRT should consider obtaining their own "personal" computer. New diskettes compatible with the machine and containing

conveniently-formatted pluviometric data could again be requested from AGRHYMET. Before implementing this alternative, a computer specialist should determine the minimum memory requirements for running the model's program. My assumption is that a 16K machine would be adequate, but I'm not sure.

On the following pages, I try to show what an actual session with the computer involves, and provide some unessential listings to familiarize the user with the data files invoked. I do not however show any file editting or file manipulations. To produce new files, or to modify existing ones, the user must become familiar with the RT-11SJ monitor commands and text editor. User guides are available at the computer facility, including a reference manual for the Fortran IV language. To understand the exact meaning of each "field" in data files, the user should examine the READ and associated FORMAT statements in the Fortran program listing here provided.

Comments have been added directly to the computer printout. I hope that the reader can always distinguish the original printout from the comments, as the latter were produced by the same typewriter used for these last 3 pages.

Turn terminal on.

Turn computer on, and "boot".

```
@:
000000 000000 165212 165530
@DY
RT-11SJ   V04.00C

.DATE 4-NOV-85

.TIME 14:57
```

Type DY (all user-supplied text is shown in boxes)

The "system" diskette is in DY0:, which is initially the default DK:. Let's look at its directory to see what the diskette has stored on it.

```
.DIR DY0:
 04-Nov-85
SWAP   .SYS    25  01-Feb-82
DY     .SYS     4  01-Feb-82
PIP    .SAV    23  01-Feb-82
RT11SJ.SYS     67  01-Feb-82
FORMAT.SAV     19  01-Feb-82
LINK   .SAV    41  01-Feb-82
FORLIB.OBJ    176  29-Apr-83
SYSLIB.OBJ     47  01-Feb-82
BATCH  .SAV    26  01-Feb-82
 18 Files, 871 Blocks
 103 Free blocks
```

```
TT     .SYS     2  01-Feb-82
NL     .SYS     2  01-Feb-82
DIR    .SAV    17  01-Feb-82
DUP    .SAV    41  01-Feb-82
MACRO  .SAV    51  01-Feb-82
FORTRA.SAV   204  29-Apr-83
EDIT   .SAV    19  01-Feb-82
STARTS.COM      0
HELP   .SAV   107  01-Feb-82
```

The program/data diskette is in DY1:, which we will later make the default, or DK:. Let's look at its directory.

```
.DIRECTORY DY1:
 04-Nov-85
SOTUBA.DAT     1  28-Oct-85
YIELDP.FOR    29  04-Nov-85
YIELDM.FOR    26  04-Nov-85
MOPTI .DAT     1  04-Nov-85
VITEP .FOR    23  04-Nov-85
 9 Files, 136 Blocks
 838 Free blocks
```

```
RENDP  .FOR   27  04-Nov-85
SORGH1.DAT     1  02-Nov-85
RENDM  .FOR   27  04-Nov-85
SORGH2.DAT     1  04-Nov-85
```

The next command assigns the default drive to be the same as DY1:, thus making file references much simpler.

```
.ASS DY1: DK:
```

```
.TYPE SOTUBA.DAT
SOTUBA                                  12.70   145
 855 860 813 617 500 471 573 571 577 548 632 793 855 860
 307 317 315 288 264 258 261 272 263 246 251 283 307 317
 871 810 723 723 645 548 670 765 767 790 874 782 871 810
```

Sotuba.Dat is an example of a station file used later.

Mopti.Dat is another example, and is the one that will be used to produce the runs shown later.

```
TYPE DK:MOPTI.DAT
MOPTI (SYNOPTIC STATION)  14.52   80
 881 907 903 910 710 623 630 765 713 568 684 861 881 907
 288 316 328 312 284 272 275 284 263 229 225 269 288 316
 848 837 784 807 748 694 787 861 863 694 800 857 848 837
```

Sorghl.Dat is an example of a 'culture" file required by the program.

```
TYPE DY1:SORGH1.DAT
SILT LOAM          1000 100 150 50
SORGHO CULTIVAR:110 DAYS 30 05 25
 007 033 073 110
 040 099 060
 70 70 30 32100 280 0108
 10 35 50 020 045 010
```

Sorgh2.Dat is the file actually used in the runs that follow, and differs from Sorghl.Dat in only 2 lines:

```
TYPE SORGH2.DAT
SILT LOAM          1000 100 229 45 ------- WHC and SMFRAC changed
SORGHUM BICOLOR:110 DAYS 30 05 25
 007 033 073 110
 040 105 060   ---------------------------- KCROP values changed also.
 70 70 30 32100 280 0108
 15 35 50 020 045 010
```

The program will ask for a rainfall diskette at a certain stage. There are two series of such diskettes, a P series and a M series. Programs that use the P series end with the letter P, e.g. YIELDP.FOR and VITEP.FOR. For convenience, I have one file of each series on the following diskette.

```
DIR
 04-Nov-85
M436  .DAT     94   17-Aug-82
 2 Files, 969 Blocks
 5 Free blocks
```

PMAL03.DAT 875 06-Jun-85

Notice that the PMAL03.Dat file is <u>very</u> long, since it contains many stations.

```
EDIT M436.DAT
*R$$
*26L

$$
```

Here, I use the editor to look at the file, rather than listing it with a TYPE command.

```
2704361950011
2704361950012
2704361950021
2704361950022
2704361950031
2704361950032
2704361950041
2704361950042
2704361950051
2704361950052
2704361950061  30     271          41      5          50              29
2704361950062                      118 215   8   5     116     11  91
2704361950071                              200           9
2704361950072  85      66          115             570 236         241 330
2704361950081     310 231                   42          132 164     218 313  25
2704361950082  56  12  56 195   2 120  87 720 284  50  49          762  90
2704361950091          516 257 191     115      55      43     145 326     451
2704361950092 415                     237  30     255                     15
2704361950101- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10
2704361950102- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10
2704361950111- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10
2704361950112- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10
2704361950121- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10
2704361950122- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10
2704361951011- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10
2704361951012- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10- 10
*
^C$$
```

I used Control C, esc, esc, to get out of EDIT, since the diskette had no spare room for producing a backup copy. The data fields with "-10" indicate missing values.

```
EDIT PMAL03.DAT
*R$$
*

14L$$
```

Similarly, let's look at the big P series file. 'E054' is the station code. Mopti's data begins much farther down the file, since its code is E064. Note: These station codes are not of the same type as in the M series; cross-references for codes are given later.

```
E05496601
E05496602
E05496603
E05496604
E05496605          0172
E05496606                                                  0195
E05496607                                                     0421
E05496608             0152                              0107
E05496609             03150165        0318    0485          0008        019
E05496610          0272        0276        0199                      0094018
E05496610020202340034          03850387                      0272
E05496611
E05496612
E05496701
E05496702
```

"966" refers to 1966, the first year of data. The last 2 digits of the first field give the month number. Then follow 31 fields for daily rainfall, i.e. each line represents an entire month. Only a portion of each line can be shown here, since the line is 133 characters long. Blanks, of course, represent days with no rain.

```
22A$12L$$
E05496711
E05496712
E05496801
E05496802
E05496803
E05496804      0277
E05496805
E05496806                                  0382                     008
E05496807      01520355          00040045                     0340  016
E05496808015200270092   0310        0175                       0121
E05496809          0215
E05496810          0149                                        01570004
*
^C$$
```

The following is a listing of the main program, in a version with English comments and output statements, and with input formats and logic compatible with the P series of rainfall data diskettes. The comparable French version is named RENDP.FOR.

```
TYPE YIELDP.FOR

C  PROGRAM TO CALCULATE MAXIMUM THEORETICAL CROP YIELDS,
C  BASED ONLY ON CLIMATE AND SOIL PHYSICAL FACTORS.
C  MODEL CLOSELY FOLLOWS:
C    FAO, 1978. REPORT ON THE AGRO-ECOLOGICAL ZONES PROJECT.
C      VOL.1: METHODOLOGY AND RESULTS FOR AFRICA.  WORLD SOIL
C      RESOURCES REPORT NO.48, FAO, ROME, 158P.
C  PROGRAM WRITTEN BY:
C      STEVEN L. WOODALL
C      USAID/SECID
C      PROJECT INVENTAIRE DES RESSOURCES TERRESTRES
C      SOTUBA, BAMAKO, REPUBLIQUE DU MALI
C      2 NOVEMBER, 1985
C  ------------------------------------------------------------------
      PROGRAM YIELDP  !USE ONLY WITH PMALXX.DAT RAINFALL SERIES
      REAL*8 CROP,SOIL,LOC,LOCAT,CULT,PLUV,WHEN
      REAL*4 TCLASS,PS,KCROP,KMAX,KBASE,KTERM,KGROW,
     *KMAIN,LAI,NUM,NPP,KANGLE,LAT,KM
      INTEGER DA,DA1,DA2,DUR,ENDDAY,GERM,RETARD,
     *SOW,SOWDAT,YEAR,YR,STATN,STA,FIRST
      DIMENSION DUR(6),SOWDAT(6),ENDDAY(14),RTOP10(14),
     *RTOP20(14),RTOP(14), HSP10(14), HSP20(14), HSP(14),HBSA(14),
     *PET(14),TEMP(14),BC10(14),BC20(14),BO10(14),BO20(14),
     *BCC(14),BOO(14),RP(397),RA(397),HBS(397),ETP(397),
     *TMEAN(397),BC(397),BO(397),
     *PG(365),SM(365),ETA(365),ERATIO(365),SEEP(365),
     *LOC(3),SOIL(2),CROP(3),LOCAT(2),CULT(2),PLUV(2),
     *WHEN(2)
      DATA ENDDAY/1,32,62,93,123,154,185,215,246,276,307,
     *338,366,397/
      DATA RTOP10/903.,926.,916.,900.,904.,915.,907.,864.,
     *800.,753.,779.,844.,903.,926./
      DATA RTOP20/851.,925.,959.,966.,959.,938.,878.,787.,
     *685.,623.,654.,753.,851.,925./
      DATA  HSP10/12.07,12.35,12.58,12.70,12.65,12.45,
     *12.18,11.91,11.68,11.54,11.58,11.82,12.07,12.35/
      DATA  HSP20/12.02,12.60,13.08,13.33,13.23,12.83,12.26,11.70,
     *11.19,10.93,11.06,11.49,12.02,12.60/
      DATA BC10/422.,437.,440.,440.,440.,439.,431.,411.,385.,
     *370.,376.,401.,422.,437./
      DATA BC20/407.,439.,460.,468.,465.,451.,425.,387.,348.,
     *325.,334.,371.,407.,439./
      DATA BO10/225.,234.,236.,235.,236.,235.,230.,218.,203.,193
     *.,197.,212.,225.,234./
      DATA BO20/215.,235.,246.,250.,249.,242.,226.,203.,178.,
     *164.,170.,193.,215.,235./
      DATA PG/365*000.0/
      CALL DATE(WHEN)
      PAUSE 'RETURN, TYPE NAME OF STATION FILE, E.G. BAMAKO.DAT, THEN
     *RETURN'
      ACCEPT 5,LOCAT
    5 FORMAT(A8,A2)
      OPEN (UNIT=1,TYPE='OLD',NAME=LOCAT)
```

45

```
      READ(1,10) (LOC(I),I=1,3),LAT,LNMS
      READ(1,12) (PET(K),K=1,14)
      READ(1,14) (TEMP(K),K=1,14)
      READ(1,16) (HBSA(K),K=1,14)
      CLOSE(UNIT=1)
 35   K=2    !K=1 IN MARCH AND J=1 ON 15 MARCH
      DO 50 J=1,397    !ASSIGN MID-MONTH VALUES TO EACH DAY IN MONTH
      IF(J.EQ.(ENDDAY(K)-(ENDDAY(K)-ENDDAY(K-1))/2+1)) K=K+1
      ETP(J)=PET(K)
      TMEAN(J)=TEMP(K)
 50   HBS(J)=HBSA(K)
      X=(LAT-10.)/10.
      DO 60 K=1,14    !INTERPOLATE FOR LATITUDE
      RTOP(K)=RTOP10(K)+X*(RTOP20(K)-RTOP10(K))
       HSP(K)= HSP10(K)+X*( HSP20(K)- HSP10(K))
      BCC(K)=BC10(K)+X*(BC20(K)-BC10(K))
 60   BOO(K)=BO10(K)+X*(BO20(K)-BO10(K))

      K=2
      DO 70 J=1,397    !INTERPOLATE DAILY VALUES FROM MIDMONTH VALUES
      IF (J.EQ.ENDDAY(K)) K=K+1
      DENOM=ENDDAY(K)-ENDDAY(K-1)
      NUM=J-ENDDAY(K-1)
      HN= HSP(K-1)+NUM*( HSP(K)- HSP(K-1))/DENOM
      REX=RTOP(K-1)+NUM*(RTOP(K)-RTOP(K-1))/DENOM
      RP(J)=(.25+.50*.75)*REX
      RA(J)=(.25+.50*HBS(J)/HN)*REX
      BC(J)=BCC(K-1)+NUM*(BCC(K)-BCC(K-1))/DENOM
 70   BO(J)=BOO(K-1)+NUM*(BOO(K)-BOO(K-1))/DENOM
      DO 75 I=1,365    !MAKE I=1 ON 1 APRIL
      ETP(I)=ETP(I+17)
      TMEAN(I)=TMEAN(I+17)
      HBS(I)=HBS(I+17)
      RP(I)=RP(I+17)
      RA(I)=RA(I+17)
      BC(I)=BC(I+17)
 75   BO(I)=BO(I+17)
C***OUTPUT CLIMATIC ASSUMPTIONS OF STATION
      TYPE 77,LOC,WHEN,LAT,LNMS
      TYPE 78
      DO 80 I=1,12
      MM=INT(15+(I-1)*30.5)    !MM IS APPROX. MIDDLE OF EACH MONTH
 80   TYPE 81,I,TMEAN(MM),RP(MM),HBS(MM),RA(MM),ETP(MM),
     *BC(MM),BO(MM)
 82   TYPE 950
 950  FORMAT(1H0,77('-'))
      PAUSE 'RETURN, TYPE NAME OF CULTURE FILE, E.G. SORGH1.DAT,
     *THEN RETURN'
      ACCEPT 9, CULT
 9    FORMAT (A8,A2)
      IF(CULT(1).EQ.'') GO TO 1100
      OPEN(UNIT=1,TYPE='OLD',NAME=CULT)
      READ(1,83)(SOIL(I),I=1,2),RDMAX,RDBASE,WHC,SMFRAC
      SMMAX=RDMAX*WHC
      READ(1,85) (CROP(I),I=1,3),LAI,KANGLE,HINDEX
```

```
      READ(1,86) GERM,DA1,DA2,MAT
      READ(1,87) KBASE,KMAX,KTERM
      READ(1,88) FSM,FSCOR,OPTMIN,OPTMAX,PARMIN,KGROW,KMAIN
      READ(1,89) CRIT0,CRIT1,CRIT2,EFF1,EFF2,EFF3
      CLOSE(UNIT=1)
      TYPE 90, SOIL,RDMAX,WHC,SMFRAC
      TYPE 91, CROP,LAI,KANGLE,HINDEX
      TYPE 92, GERM,DA1,DA2,MAT
      TYPE 93, KBASE,KMAX,KTERM
      TYPE 94, FSCOR,OPTMIN,OPTMAX,PARMIN,KGROW,KMAIN
      TYPE 95, CRIT0,CRIT1,CRIT2,EFF1,EFF2,EFF3
      PAUSE 'INSERT RAIN DISKETTE (PMALXX.DAT) IN DY1: THEN RETURN'
      PAUSE 'RETURN,TYPERAINFILENAME(PMALXX.DAT),SPACEONCE,
     *TYPESTATIONCODE(XXX),RETURN'
      ACCEPT 99, FLUV,STATN
   99 FORMAT(A8,A2,1X,3I)
      OPEN(UNIT=1,TYPE='OLD',NAME=FLUV)
      TYPE 547
  547 FORMAT(1X,77('-'))
C***BEGINNING OF ANNUAL LOOP
   97 SOW=0
      DO 96 I=1,6
      DUR(I)=0
   96 SOWDAT(I)=-
      RETARD=0
      OLDSM=0.
      TCLASS='OPT
      NMV=0
  104 LAST=0
      J=0
      K=2
  105 J=J+1  !ESTABLISH DAILY RAINFALL FOR MONTH J
      K=K+1
      FIRST=LAST+1
      LAST=LAST+ENDDAY(K)-ENDDAY(K-1)
  106 READ(1,108,END=1000,ERR=995) STA,YR,MOIS,(PG(I),I=FIRST,LAST)
      IF((J.EQ.1).AND.(STA.NE.STATN)) GO TO 106
      IF((J.EQ.1).AND.(MOIS.NE.04)) GO TO 106
      IF((STA.NE.STATN).AND.(J.NE.1)) GO TO 1000
      DO 110 I=FIRST,LAST
      IF(PG(I).GE.0.) GO TO 110
      PG(I)=0  !MISSING VALUES SET TO ZERO.
      NMV=NMV+1
  110 CONTINUE
      IF(J.LT.12) GO TO 105
      YEAR=YR-1
      IF(MOIS.NE.3) TYPE 112,YEAR,YR,MOIS
  112 FORMAT(1H0,'ERROR IN PRECIP INPUT.  YEAR AT MONTH 1 IS 19'
     *,I2,'; YEAR AT MONTH 12 IS 19',I2,';'/
     *' BUT CALENDAR MONTH AT MONTH 12 IS ',I2,', RATHER THAN 3
     *(MARCH).')
      DO 120 I=1,365
  120 SEEP(I)=0.
      I=0  !BEGIN SEARCH FOR SOWING DATE
  115 I=I+1
      IF(I.GT.(365-MAT-GERM)) GO TO 800
```

```
      SPG=0.
      SETP=0.
      II=MAX0(1,I-9)
      DO 125 KK=II,I
      SPG=SPG+PG(KK)
 125  SETP=SETP+ETP(KK)
      IF(SPG.LT.(0.5*SETP)) GO TO 115
      LGC=1
      SOW=SOW+1
      IF(SOW.GT.6) GO TO 820
      SOWDAT(SOW)=I   !SOWING OCCURS ON DAY I
      ESMMAX=RDBASE*WHC
      ESM=ESMMAX  !TOP LAYER FULLY WETTED AT SOWING, BUT
      RD=RDBASE
      SM(I)=OLDSM+ESM   !BUT LOWER LAYERS ARE DRY (OLDSM=0
      CUMRED=0.
      CMRED1=0.
      CMRED2=0.
      CMRED3=0.
 150  I=I+1
      LGC=LGC+1
      SM(I)=SM(I-1)   !WATER BALANCE PRIOR TO GERMINATION
      IF(PG(I).LT.1.) GO TO 160
      ESM=ESM+PG(I)
      SM(I)=SM(I)+PG(I)
      IF(SM(I).LE.SMMAX) GO TO 155
      SEEP(I)=SM(I)-SMMAX
      SM(I)=SMMAX
 155  IF(ESM.GT.ESMMAX) ESM=ESMMAX
 160  ETC=KBASE*ETP(I)
      ETA(I)=ETC*ESM/ESMMAX
      ESM=ESM-ETA(I)
 180  IF(LGC.LT.GERM) GO TO 150
      DA=0  !ON DAY OF GERMINATION, DA=1
 200  I=I+1
      LGC=LGC+1
      DA=DA+1
      SM(I)=SM(I-1)
      IF(DA.GT.DA1) GO TO 230
      KCROP=KBASE+(KMAX-KBASE)*DA/DA1
      OLDRD=RD
      RD=RDBASE+(RDMAX-RDBASE)*DA/DA1
      ESMMAX=RD*WHC
      ESMINC=(RD-OLDRD)*WHC   !NEXT STMTS BRING IN DEEPER STORED MOISTURE
      IF(ESMINC.GT.(SM(I)-ESM)) GO TO 210
      ESM=ESM+ESMINC
      GO TO 250
 210  ESM=SM(I)
      GO TO 250
 230  IF(DA.LE.DA2) GO TO 250
      KCROP=KMAX-(KMAX-KTERM)*(DA-DA2)/(MAT-DA2)
 250  ESM=ESM+PG(I)
      SM(I)=SM(I)+PG(I)
      IF(ESM.LE.ESMMAX) GO TO 270
      ESM=ESMMAX
      IF(SM(I).LE.SMMAX) GO TO 270
      SEEP(I)=SM(I)-SMMAX
      SM(I)=SMMAX
```

```
 270  ETC=KCROP*ETP(I)
      ETA(I)=ETC*AMIN1(1.,ESM/(ESMMAX*(1.-SMFRAC)))
      ESM=ESM-ETA(I)
      SM(I)=SM(I)-ETA(I)
      ERATIO(I)=ETA(I)/ETC
      IF(DA.GT.DA1) GO TO 300
      IF(ERATIO(I).GE.CRIT1) GO TO 320
      IF(ERATIO(I).LT.CRIT0) GO TO 290  !FALSE START, MAY RESOW
      IF(RETARD.GE.10) GO TO 285
      DA=DA-1
      RETARD=RETARD+1
      GO TO 320
 285  CMRED1=CMRED1+EFF1  !REDUCTIONS BEGIN AFTER 10 STRESS DAYS
      GO TO 320
 290  DUR(SOW)=LGC
      RETARD=0
      C_DSM=SM(I)-RDBASE*WHC  !AFTER FALSE START, DEEP SM IS REMEMBERED
      GO TO 115
 300  IF(DA.GT.DA2) GO TO 310
      IF(ERATIO(I).GE.CRIT2) GO TO 320
      IF(ERATIO(I).LT.CRIT0) GO TO 500  !CROP FAILURE, TOO LATE TO RESOW
      CMRED2=CMRED2+EFF2
      GO TO 320
 310  CRIT3=(MAT-DA)*CRIT1/(MAT-DA2)  !CRIT3 DECREASES TOWARD HARVEST
      IF(ERATIO(I).GE.CRIT3) GO TO 320
      CMRED3=CMRED3+EFF3
 320  CONTINUE
D     TYPE 321, I,LGC,DA,PG(I),KCROP,RD,ESM,SM(I),SEEP(I),ETA(I)
D    *,ERATIO(I),RETARD,CMRED1,CMRED2,CRIT3,CMRED3
D321  FORMAT(1X,I3,2I4,F5.0,F4.1,F7.1,2F5.0,F5.1,2F4.1,I3,4F5.2)
      IF(DA.LT.MAT) GO TO 200
 500  JH=I  !BEGIN SUMMARIZING GROWING PERIOD CONDITIONS
      II=SOWDAT(SOW)
      DUR(SOW)=LGC
      CUMRP=0.
      CUMRA=0.
      CUMT=0.
      CUMBC=0.
      CUMBO=0.
      CUMPG=RDBASE*WHC
      CUMSEP=0.
      DO 600 J=II,JH
      CUMRP=CUMRP+RP(J)
      CUMRA=CUMRA+RA(J)
      CUMT=CUMT+TMEAN(J)
      CUMBC=CUMBC+BC(J)
      CUMBO=CUMBO+BO(J)
      CUMPG=CUMPG+PG(J)
 600  CUMSEP=CUMSEP+SEEP(J)
      TSEAS=CUMT/LGC
      PAR=0.5*CUMRA/LGC
      IF(TSEAS.LT.OPTMIN) TCLASS='COOL
      IF(TSEAS.GT.OPTMAX) TCLASS='HOT'
      IF(TCLASS.EQ.'OPT') GO TO 620
      IF(PSM.NE.PSCOR) GO TO 620
      TYPE 700, TSEAS,TCLASS,PAR
```

```
      PAUSE 'RETURN, TYPE CORRECTED VALUE FOR PSM (XX.), RETURN'
      ACCEPT 610, PSCOR
 610  FORMAT(F3.0)
 620  F=(CUMRP-CUMRA)/(0.8*CUMRP)
      BCSEAS=CUMBC/LGC
      BOSEAS=CUMBO/LGC
      ETSEAS=CUMPG-CUMSEP-SM(JH)
C***ESTABLISH GPP AT MIDDLE OF GROWTH CYCLE
      Y=(PSCOR-20.)/20.
      IF(Y.GE.0.0) GO TO 640

      GPP=F*(1.+2.5*Y)*BOSEAS+(1.-F)*(1.+Y)*BCSEAS
      IF(GPP.LT.0.) GO TO 930
      GO TO 650
 640  GPP=F*(1.+.2*Y)*BOSEAS+(1.-F)*(1.+.5*Y)*BCSEAS
 650  ADJ=1.-EXP(-KANGLE*LAI)
      GPP=GPP*ADJ
      KM=KMAIN*(0.44+.0019*TSEAS+.0010*TSEAS**2)
      NPP=(1.-KGROW)*GPP/(1.+.25*KM*MAT)
      BIOMAS=0.5*NPP*MAT
      IF(DA.LT.MAT) BIOMAS=0.  !RETEST FOR CROP FAILURE
      YLDPOT=BIOMAS*HINDEX
      CUMRED=CMRED1+CMRED2+CMRED3
      YLDACT=YLDPOT*(1.-AMIN1(1.,CUMRED))
      TYPE 675, YEAR,SOW,DA
      TYPE 680, YLDPOT,YLDACT
      TYPE 685, SOWDAT
      TYPE 690, DUR
      TYPE 705, CUMPG,CUMSEP,SM(JH),ETSEAS
      TYPE 710, RETARD,CUMRED,CMRED1,CMRED2,CMRED3
      GO TO 990
 800  TYPE 810, YEAR,I
      GO TO 990
 820  TYPE 822, SOW,I,YEAR
      GO TO 990
 930  TYPE 932, GPP
 990  GO TO 97  !THIS IS THE END OF THE ANNUAL CYCLE
 995  TYPE 996,I,STA,YR,MOIS
 996  FORMAT(' I=,STA=,YR=,MOIS=',4I6)
 000  CONTINUE   !END OF DATA IN RAIN FILE
      CLOSE(UNIT=1)
      PAUSE 'REINSERT PROGRAM DISKETTE IN DY1, THEN RETURN'
      GO TO 82   !START OVER WITH DIFFERENT CULTURE
 100  CONTINUE
  10  FORMAT(3A8,2X,F5.2,2X,I3)
  12  FORMAT(14F4.2)
  14  FORMAT(14F4.1)
  16  FORMAT(14F4.2)
  77  FORMAT(////' STATION NAME: ',3A8,7X,'DATE OF JOB: ',A8,A1/
     *' LATITUDE: ',F5.2,' DEG N'/
     *' LENGTH OF NORMAL MOIST SEASON: ',I3,' DAYS'/)
  78  FORMAT(1H0,T24,'DAILY VALUES AT MIDDLE OF MONTH'/
     *1X,T23,'(WATER YEAR BEGINS 1 APR, NOT 1 JAN)'/
     *1H0,'MONTH',T12,'TMEAN',T24,'RP',T33,'HBS',T44,'RA',T53,
     *'ETP',T64,'BC',T74,'BO'/1X,77('-')/)
  81  FORMAT(3X,I2,T12,F5.2,5X,F5.1,6X,F4.2,5X,F5.1,5X,F5.2,
     *2(5X,F5.1))
  83  FORMAT(2A8,F5.0,F4.0,F4.3,F3.2)
```

```
 85  FORMAT(3A8,2F3.1,F3.2)
 86  FORMAT(4I4)
 87  FORMAT(3F4.2)
 88  FORMAT(4F3.0,F3.2,F4.3,F5.4)
 89  FORMAT(3F3.2,3F4.3)
 90  FORMAT(/1X,77('-')/1H0,'SOIL TYPE ASSUMED: ',2A8/
    *1X,'MAXIMUM ROOTING DEPTH:  ',F5.0,' MM',6X,
    *'WATER HOLDING CAPACITY:  ',F5.3,' MM/MM'/
    *1X,'FRACTION OF SOIL MOISTURE THAT IS READILY AVAILABLE:
    *,F4.2)
 91  FORMAT(1H0,'CROP:  ',3A8/
    *1X,'LAI: ',F3.1,20X,'CANOPY RADIATION EXTINCTION COEFF.:
    *',F3.1/
    *1X,'YIELD FRACTION OF TOTAL BIOMASS:  ',F4.2/)
 92  FORMAT(1X,'DAYS REQUIRED FOR SEED GERMINATION:  ',I2/
    *1X,'DAYS (AFTER GERMINATION) TO REACH FULL SITE OCCUPANCY:
    * ',I3/1X,'DAYS (AFTER GERMINATION) TO OVULE FERTILIZATION:
    * ',I3/1X,'DAYS (AFTER GERMINATION) TO REACH FULL MATURITY:
    * ',I3,' (HARVEST)'/)
 93  FORMAT(1X,'CROP COEFFICIENTS FOR ET:'/5X,'INITIAL =
    *F4.2,8X,'MAXIMUM = ',F4.2,8X,'TERMINAL = ',F4.2)
 94  FORMAT('0ASSUMED MAX PHOTOSYNTHESIS: ',F3.0,
    *' KG/HA(LEAF SURFACE)/HR'/
    *' MIN AND MAX TEMPS (DEG C) OF OPTIMAL RANGE: '
    *F3.0,2X,F3.0/1X,'INTENSITY OF PAR NEEDED FOR SATURATION: ',
    *F3.1,' CAL/CM2/MIN'/
    *1X,'RESPIRATION COEFFICIENTS:  GROWTH=',F5.3,
    *'  MAINTENANCE=',F6.4)
 95  FORMAT(1H0,'ERATIO TRIGGERING CROP FAILURE (BEFORE DA2):
    * ',F4.2/1X,'ERATIO THRESHOLDS FOR STRESS DAYS:  ',
    *F4.2,' (TO DA1);  ',F4.2,' (FROM DA1 TO DA2)'/
    *1X,'FRACTIONAL REDUCTION OF YIELD FOR EACH STRESS DAY:'
    */5X,F4.2,' (TO DA1);  ',F4.2,' (FROM DA1 TO DA2);  ',
    *F4.2,' (FROM DA2 TO HARVEST)'/1X,77('-'))
108  FORMAT(1X,I3,1X,I2,I2,31F4.1)
675  FORMAT(1H0,'YEAR:  19',I2,5X,'NUMBER OF SOWINGS: '
    *,I1,4X,'DEVELOPMENTAL AGE ACHIEVED: ',I3,' DAYS'/)
680  FORMAT(' CROP YIELD (KG/HA):'/6X,F5.0,' (NO MOISTURE CONSTRAI
    *NTS )'/6X,F5.0,' (CORRECTED FOR SOIL WATER STRESS)'/)
685  FORMAT(' DATE OF SOWINGS:'/6X,I3,5(7X,I3))
690  FORMAT(' DURATION OF GROWTH PERIOD(DAYS):'/6X,I3,5(7X,I3)/)
700  FORMAT(1H0,'MEAN SEASONAL TEMP:  ',F4.1,' DEG C',7X,
    *'TCLASS:  ',A4/' MEAN SEASONAL PAR:  ',F4.0)
705  FORMAT(' SEASONAL RAINFALL TOTAL: ',F5.0/
    *' SEEPAGE PAST ROOT ZONE: ',F4.0/' AVAILABLE MOISTURE IN R
    *OOT ZONE AT HARVEST: ',F4.0/' ASSUMED ACTUAL SEASONAL ET:
    *',F5.0/)
710  FORMAT(' DAYS RETARDED DUE TO STRESS:  ',I2/
    *' TOTAL YIELD REDUCTION DUE TO STRESS:  ',F4.2/
    *3X,'REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:
    *,3(F5.3,2X)/1H0,77('-'))
810  FORMAT(1H0,'YEAR 19',I2,' HAD NO SOWINGS BEFORE DAYNO ',I3/
    *' INSUFFICIENT TIME LEFT FOR FULL GROWTH CYCLE')
822  FORMAT(1H0,I1,' SOWINGS HAD OCCURRED BY DAYNO ',I3,
    *' IN 19',I2)
932  FORMAT(1H0,'GROSS PHOTOSYNTHESIS WAS  ',F6.2,'; RADIATION
    *PROBABLY MISCALCULATED')
     STOP 'END OF JOB'
     END
```

```
FORTRAN/RECORD:150/SHOW:Q/LIST:TT:  ANGLAY.FOR
YIELDP
```

ANGLAY was a former name of YIELDP, and will not be found on any diskette.

This statement compiles the file called ANGLAY.FOR; since the rain data will need a line length longer than the default (132), 150 spaces are requested (133 may have been enough); I've asked to be shown only error messages; and I've told the computer to send those messages to the teletype (the basic terminal).

```
LINK ANGLAY,DY0:SYSLIB,DY0:FORLIB
```

The compiled object module, named ANGLAY.OBJ, is then linked with other object modules stored on the system diskette, producing a single file called ANGLAY.SAV, which is run by the following statement.

```
RUN ANGLAY

PAUSE -- RETURN, TYPE NAME OF STATION FILE, E.G. BAMAKO.DAT, THENRETURN

MOPTI.DAT
```

"Prompts" written under control of the program have instructions that should be followed precisely.

```
STATION NAME: MOPTI (SYNOPTIC STATION)        DATE OF JOB: 04-NOV-85
LATITUDE: 14.52 DEG N
LENGTH OF NORMAL MOIST SEASON:  80 DAYS
```

DAILY VALUES AT MIDDLE OF MONTH
(WATER YEAR BEGINS 1 APR, NOT 1 JAN)

MONTH	TMEAN	RP	HBS	RA	ETP	BC	BO
1	32.80	578.5	7.84	522.5	9.03	437.9	234.5
2	31.20	584.6	8.07	528.6	9.10	449.0	240.5
3	28.40	581.1	7.48	500.3	7.10	452.7	241.8
4	27.20	580.5	6.94	481.8	6.23	451.3	241.9
5	27.50	578.4	7.87	519.9	6.30	444.4	238.2
6	28.40	559.3	8.61	538.8	7.65	428.8	228.5
7	26.30	518.2	8.63	510.1	7.13	400.2	211.2
8	22.90	469.1	6.94	414.7	5.68	369.3	192.3
9	22.50	433.9	8.00	420.1	6.84	349.7	179.9
10	26.90	451.0	8.57	453.0	8.61	356.8	184.6
11	28.80	500.2	8.48	491.1	8.81	386.5	202.8
12	31.60	550.6	8.37	525.9	9.07	416.0	220.9

```
PAUSE -- RETURN, TYPE NAME OF CULTURE FILE, E.G. SORGH1.DAT,THEN RETURN

SORGH2.DAT
```

The station and culture files are on the same diskette as the program, so requesting these files is easy.

```
SOIL TYPE ASSUMED: SILT LOAM
MAXIMUM ROOTING DEPTH:  1000. MM      WATER HOLDING CAPACITY:  0.229 MM/MM
FRACTION OF SOIL MOISTURE THAT IS READILY AVAILABLE:  0.45

CROP:  SORGHUM BICOLOR:110 DAYS
LAI: 3.0                    CANOPY RADIATION EXTINCTION COEFF.: 0.5
YIELD FRACTION OF TOTAL BIOMASS:  0.25

DAYS REQUIRED FOR SEED GERMINATION:   7
DAYS (AFTER GERMINATION) TO REACH FULL SITE OCCUPANCY:  33
DAYS (AFTER GERMINATION) TO OVULE FERTILIZATION:  73
DAYS (AFTER GERMINATION) TO REACH FULL MATURITY: 110 (HARVEST)

CROP COEFFICIENTS FOR ET:
    INITIAL = 0.40        MAXIMUM = 1.05        TERMINAL = 0.60

ASSUMED MAX PHOTOSYNTHESIS: 70. KG/HA(LEAF SURFACE)/HR
MIN AND MAX TEMPS (DEG C) OF OPTIMAL RANGE: 30.  32.
INTENSITY OF PAR NEEDED FOR SATURATION: 1.0 CAL/CM2/MIN
RESPIRATION COEFFICIENTS:  GROWTH=0.280  MAINTENANCE=0.0108

ERATIO TRIGGERING CROP FAILURE (BEFORE DA2): 0.15
ERATIO THRESHOLDS FOR STRESS DAYS:  0.35 (TO DA1);  0.50 (FROM DA1 TO DA2)
FRACTIONAL REDUCTION OF YIELD FOR EACH STRESS DAY:
    0.02 (TO DA1);  0.05 (FROM DA1 TO DA2);  0.01 (FROM DA2 TO HARVEST)

PAUSE -- INSERT RAIN DISKETTE (PMALXX.DAT) IN DY1: THEN RETURN
```

(But the rain file is on another diskette.)

```
PAUSE -- RETURN,TYPERAINFILENAME(PMALXX.DAT),SPACEONCE,TYPESTATIONCODE(XXX),RETU
```

SV

```
---------------------------------------------------------------------------
MEAN SEASONAL TEMP:  26.9 DEG C        TCLASS:  COOL
MEAN SEASONAL PAR:  253.
PAUSE -- RETURN, TYPE CORRECTED VALUE FOR PSM (XX.), RETURN

60.
---------------------------------------------------------------------------
YEAR:  1966     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED: 110 DAYS

CROP YIELD (KG/HA):
     4493. (NO MOISTURE CONSTRAINTS )
      449. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
     109       -99       -99       -99       -99       -99
DURATION OF GROWTH PERIOD(DAYS):
     117         0         0         0         0         0

SEASONAL RAINFALL TOTAL:  432.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  25.
ASSUMED ACTUAL SEASONAL ET:  407.

DAYS RETARDED DUE TO STRESS:   0
TOTAL YIELD REDUCTION DUE TO STRESS:  0.90
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.000  0.900  0.000
---------------------------------------------------------------------------
YEAR:  1967     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED: 110 DAYS

CROP YIELD (KG/HA):
     4513. (NO MOISTURE CONSTRAINTS )
     4513. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
     102       -99       -99       -99       -99       -99
DURATION OF GROWTH PERIOD(DAYS):
     117         0         0         0         0         0

SEASONAL RAINFALL TOTAL:  461.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  14.
ASSUMED ACTUAL SEASONAL ET:  447.

DAYS RETARDED DUE TO STRESS:   0
TOTAL YIELD REDUCTION DUE TO STRESS:  0.00
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.000  0.000  0.000
---------------------------------------------------------------------------
YEAR:  1968     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED: 110 DAYS

CROP YIELD (KG/HA):
     4527. (NO MOISTURE CONSTRAINTS )
     2490. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
      85       -99       -99       -99       -99       -99
DURATION OF GROWTH PERIOD(DAYS):
     118         0         0         0         0         0

SEASONAL RAINFALL TOTAL:  386.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  22.
ASSUMED ACTUAL SEASONAL ET:  364.

DAYS RETARDED DUE TO STRESS:   1
TOTAL YIELD REDUCTION DUE TO STRESS:  0.45
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.000  0.450  0.000
---------------------------------------------------------------------------
YEAR:  1969     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED: 110 DAYS

CROP YIELD (KG/HA):
     4523. (NO MOISTURE CONSTRAINTS )
     4319. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
      98       -99       -99       -99       -99       -99
DURATION OF GROWTH PERIOD(DAYS):
     117         0         0         0         0         0

SEASONAL RAINFALL TOTAL:  495.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  22.
ASSUMED ACTUAL SEASONAL ET:  473.

DAYS RETARDED DUE TO STRESS:   0
TOTAL YIELD REDUCTION DUE TO STRESS:  0.05
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.000  0.045  0.000
```

Normally, the user will not see this section, but it's good to know that it's there.

--Provision has been made for up to 6 sowings; -99 is the initial value.

See Part II of report for explanation of the meaning of each output.

(I've skipped some of the years to save pages.)

```
---------------------------------------------------------------------------
YEAR:  1976     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED: 110 DAYS

CROP YIELD (KG/HA):
     4516. (NO MOISTURE CONSTRAINTS )
     2280. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
      60        -99        -99        -99        -99        -99
DURATION OF GROWTH PERIOD(DAYS):
     126         0          0          0          0          0

SEASONAL RAINFALL TOTAL:  456.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  74.
ASSUMED ACTUAL SEASONAL ET:  382.

DAYS RETARDED DUE TO STRESS:   9
TOTAL YIELD REDUCTION DUE TO STRESS:  0.50
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.000  0.495  0.000
---------------------------------------------------------------------------

YEAR:  1977     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED:  67 DAYS

CROP YIELD (KG/HA):
        0. (NO MOISTURE CONSTRAINTS )
        0. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
     120        -99        -99        -99        -99        -99
DURATION OF GROWTH PERIOD(DAYS):
      74         0          0          0          0          0

SEASONAL RAINFALL TOTAL:  275.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  18.
ASSUMED ACTUAL SEASONAL ET:  258.

DAYS RETARDED DUE TO STRESS:   0
TOTAL YIELD REDUCTION DUE TO STRESS:  1.04
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.000  1.035  0.000
---------------------------------------------------------------------------

YEAR:  1978     NUMBER OF SOWINGS: 1    DEVELOPMENTAL AGE ACHIEVED: 110 DAYS

CROP YIELD (KG/HA):
     4523. (NO MOISTURE CONSTRAINTS )
        0. (CORRECTED FOR SOIL WATER STRESS)

DATE OF SOWINGS:
      69        -99        -99        -99        -99        -99
DURATION OF GROWTH PERIOD(DAYS):
     127         0          0          0          0          0

SEASONAL RAINFALL TOTAL:  367.
SEEPAGE PAST ROOT ZONE:   0.
AVAILABLE MOISTURE IN ROOT ZONE AT HARVEST:  64.
ASSUMED ACTUAL SEASONAL ET:  303.

DAYS RETARDED DUE TO STRESS:  10
TOTAL YIELD REDUCTION DUE TO STRESS:  2.10
  REDUCTIONS IN FIRST, SECOND, AND THIRD CROP PHASES:  0.300  1.800  0.000
---------------------------------------------------------------------------
PAUSE -- REINSERT PROGRAM DISKETTE IN DY1, THEN RETURN

---------------------------------------------------------------------------
PAUSE -- RETURN, TYPE NAME OF CULTURE FILE, E.G. SORGH1.DAT,THEN RETURN

[b]

STOP -- END OF JOB
```

This year had a complete crop failure.

This year, the crop completed it's life cycle, but the stress was so great, that yield was reduced to zero.

End of data in the rain file has thus been reached.

If user wishes to look at another crop or soil, it can be done at this point. To end run, give a blank line.

Note: Other stations, and therefore other rain files, require totally new runs. But, there is no need to recompile and relink.

Since the teletype terminal is so slow, the following version of the program (VITEP.FOR) was created to reduce the amount of printing. This example serves to remind the user that he should reformat the output to meet his precise needs.

```
.FORTRAN/RECORD:150/SHOW:O/LIST:TT:  VITEP.FOR
RENDP

.LINK VITEP,DYO:SYSLIB,DYO:FORLIB

.RUN VITEP

PAUSE -- RETOURNEZ! ENTREZ NOM DE FICHIER (STATION),E.G. SOTUBA.DAT! RETOURNEZ

MOPTI.DAT



--------------------------------------------------------------------------------

NOM DE STATION: MOPTI (SYNOPTIC STATION)          DATE ACTUELLE: 04-NOV-85
LATITUDE: 14.52 DEG N
DUREE DE SAISON HUMIDE NORMALE:  80 JOURS


--------------------------------------------------------------------------------
PAUSE -- RETOURNEZ! ENTREZ NOM DE FICHIER (CULTURE),E.G. SORGH1.DAT! RETOURNEZ

SORGH2.DAT

--------------------------------------------------------------------------------

SILT LOAM            RDMAX:1000.MM   WHC:0.229   SMFRAC:0.45
SORGHUM BICOLOR:110 DAYS   LAI:3.0   HINDEX:0.25
PHENOLOGY:    7   33   73   110
KCROP:  0.40  1.05  0.60
CRIT:  0.15  0.35  0.50     EFF:  0.02  0.05  0.01
PAUSE -- SUBSTITUEZ DISQUE PLUVIOMETRIQUE A DY1:! RETOURNEZ

ENTREZ NOM DE FICHIER OCCUPANT DISQUE PLUVIOMETRIQUE, (PMALXX.DAT)!
 AVANCEZ UNE ESPACE! ENTREZ NUMERO DE STATION (XXX)! RETOURNEZ
PMAL03.DAT 064
--------------------------------------------------------------------------------

TEMPERATURE DE SAISON: 26.9 DEG C        TCLASS: BAS
'PAR' MOYENNE DE SAISON: 253.
PAUSE -- RETOURNEZ! ENTREZ VALEUR CORRIGEE DE PSM (XX.)! RETOURNEZ

60.

1966  YA= 449.  YP=4493.  S=1  SDATE=109  DA=110

1967  YA=4513.  YP=4513.  S=1  SDATE=102  DA=110

1968  YA=2490.  YP=4527.  S=1  SDATE= 85  DA=110

1969  YA=4319.  YP=4523.  S=1  SDATE= 98  DA=110

1970  YA=1873.  YP=4513.  S=1  SDATE= 58  DA=110

1971  YA=3454.  YP=4515.  S=1  SDATE=101  DA=110

1972  YA=   0.  YP=   0.  S=1  SDATE= 64  DA= 40

1973  YA=   0.  YP=4522.  S=1  SDATE= 68  DA=110

1974  YA=1403.  YP=4527.  S=1  SDATE= 87  DA=110

1975  YA=4320.  YP=4524.  S=1  SDATE= 96  DA=110

1976  YA=2280.  YP=4516.  S=1  SDATE= 60  DA=110

1977  YA=   0.  YP=   0.  S=1  SDATE=120  DA= 67

1978  YA=   0.  YP=4523.  S=1  SDATE= 69  DA=110
PAUSE -- SUBSTITUEZ DISQUE PROGRAMME A DY1:! RETOURNEZ


--------------------------------------------------------------------------------
PAUSE -- RETOURNEZ! ENTREZ NOM DE FICHIER (CULTURE),E.G. SORGH1.DAT! RETOURNEZ


STOP -- LE FIN
```

CROSS-REFERENCE LIST OF STATIONS IN MALI'S METEOROLOGICAL NETWORK

1=ORSTOM
2=Mali's synoptic network
3=ASECNA
4=AGRHYMET
5=Latitude (D,M)
6=Longitude (D,M)
7=Altitude (meters)
8=?
9=?

1	2	3	4	5	6	7	8	9	STATION NAME
27000399999E			0270001	1930	52	435939		1027	AGUELHOK
27027099999E			0270002	1258	-722	320917		1027	KOULIKORO
27004599999E			0270003	1310	-855	320951		5027	BANGASSI
27041499999E			0270004	1434	-1058	60951		4027	SEGALA
27008799999E			0270005	1419	-459	276936		5027	DIA
27033799999E			0270006	1252	-827	350954		4027	NEGALA
27002999999E			0270007	1238	-801	331954		5027	BAMAKO VILLE
27048199999E		178	270008	1124	-715	332962		6027	ZANTIEBOUGOU
27007099999E		149	270009	1232	-459	310951		9227	BOBOLA ZANGASSO
27041099999E			0270010	1236	-1124	150919		7027	SATADOUGOU
27001199999E			0270011	1854	-333	280926		6027	ARAOUANE
27033899999E			0270012	1305	-549	280951		9027	NEGUENA
27014199999E			0270013	1602	4	263954		5027	GABERO
27040699999E		132	270014	1243	-727	355954		4027	SANTIGUILA
27043799999E			0270015	1048	-710	345970		3027	SOUROUKOULA
27044261202E			4270016	2012	59	493947	11	1127	TESSALIT
27022061214E			8270017	1826	121	458923		1127	KIDAL
27003199999E		11	270018	1702	-124	259919		7027	BAMBA
27007999999E		12	270019	1657	-21	273926		1027	BOUREM
27016099999E		14	270020	1653	-156	266926		1027	GOURMA-RHAROUS
27045461223E		16	270021	1643	-300	263897		0127	TOMBOUCTOU
27017899999E		17	270022	1642	-259	267923		1027	KABARA
27015499999E		19	270023	1625	-340	269919		6027	GOUNDAM
27010399999E		20	270024	1616	-324	265935	10	0027	DIRE
27014561226E		21	270025	1616	-3	258919		8127	GAO
27046099999E		23	270026	1608	-345	262961		3027	TONKA (LAC HORO)
27016699999E		24	270027	1559	-8	254966		1027	HAOUSSA-FOULANE
27034399999E		25	270028	1556	-359	271919		7027	NIAFUNKE
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