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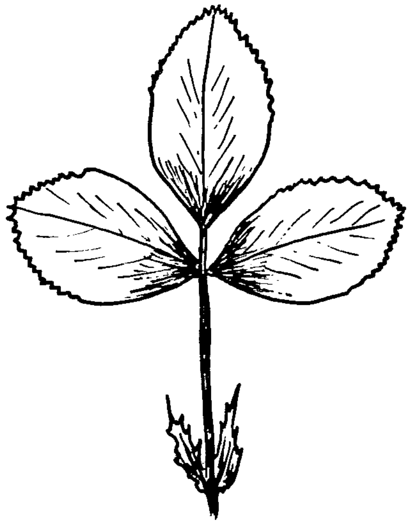

GROWTH MODELS

ALSIM 1

(LEVEL 2)

User's Manual

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ALSIM 1 (LEVEL 2) - User's Manual[1]

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ABSTRACT

ALSIM 1 (LEVEL 2) is a dynamic computer simulation model of alfalfa (*Medicago sativa* L.) growth and management written in the computer simulation language CSMP III. The model was developed primarily for studies of the management of defoliating pests of the alfalfa agro-ecosystem. It is a refinement of ALSIM 1 (LEVEL 1), and for most applications it should be used in preference to LEVEL 1. The main improvement in LEVEL 2 is a soil water budget allowing for simulation of the effects of limiting soil water supply on alfalfa growth. Under most conditions, it will more accurately predict seasonal yield distributions than will LEVEL 1. Over-winter use of stored food reserves has also been added to LEVEL 2.

Input data needed for LEVEL 2 are (a) yields of leaves, stems, basal buds, and total non-structural carbohydrate reserves (TNC) at the start of simulation; (b) soil water holding capacity of the root zone; (c) dates of harvest; (d) latitude of the study location; and (e) daily weather data for solar radiation, mean air temperature, and precipitation. The model predicts the yield of alfalfa hay and the growth curves for leaves, stems, basal buds, and TNC with simulated time steps on one day. It also simulates the supply of available water in the root zone on a daily basis. The model assumes largely pure stands of alfalfa, and it does not include growth limitations caused by excess soil water content. Neither does the model predict root growth and yield, assuming a root system sufficient to extract the available water. A discussion of model development, performance, and use is included in this report. (Agron. Mimeo. 81-35. Dep. of Agronomy, Cornell Univ., Ithaca, NY 14853).

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INTRODUCTION

In 1975, ALSIM 1 (LEVEL 1) was introduced as the first member of a family of dynamic simulation models of alfalfa (*Medicago sativa* L.) production (Fick, 1975). That version has been used in studies of alfalfa weevil control (Ruesink et al., 1980) and of alfalfa harvest management (McGuckin, 1980), but its application was limited by several deficiencies. The most obvious deficiency of LEVEL 1 was an inaccurate prediction of dry matter distribution with overestimated top growth and underestimated total nonstructural carbohydrate (TNC) accumulation as the growing season progressed. Associated with this problem was the assumption that soil water conditions were optimal. For much of the non-irrigated zone of alfalfa production around the Great Lakes, that assumption is incorrect, and limited supplies of soil water often occur in the last half of the growing season (Brown and Baylor, 1973).

The ALSIM 1 (LEVEL 2) model (hereafter called "LEVEL 2") is a refinement of the LEVEL 1 version. It retains most of the basic features of LEVEL 1, and it incorporates several changes to reduce the inaccuracies of the original. The most obvious change is the addition of a soil water budget taken directly from the published model of Ritchie (1972, 1974). A water stress factor has been added to account for the physiological effects of limited soil water supply on alfalfa growth. Physiological functions controlled by photoperiod have been modified or added to LEVEL 2 to more accurately simulate the pattern of TNC accumulation and utilization. A maintenance respiration component was also included to account for overwinter use of TNC in simulations involving the winter period of alfalfa dormancy.

The LEVEL 2 version, like LEVEL 1, was developed primarily for use in the integrated management of defoliating pests (see acknowledgments). It retains direct user control of cutting management strategy and simulation timing, and it continues to use the simulation-time-step size of 1 day, compatible with many insect pest models. In summary, LEVEL 2 is an expanded and updated version of ALSIM 1 (LEVEL 1) designed to replace the LEVEL 1 version in most applications.

The purposes of this user's manual are to document and describe LEVEL 2 for potential users and students, and to record significant aspects of the development of LEVEL 2 from LEVEL 1.

DESCRIPTION

The acronym ALSIM 1 stands for ALfalfa SImulation Models with 1-day simulation time steps. The LEVEL 2 version is the second member of the series developed at Cornell University. The LEVEL 2 model describes the time-dependent growth of alfalfa herbage as well as several related elements in the alfalfa production system. Yields of plant material are expressed in units of g of dry matter per m^2 of land surface. Water in precipitation, soil storage, and evapotranspiration is measured in units of mm, i.e., mm^3 of water per mm^2 of land surface. Rates of change are expressed on a daily basis.

The relational diagram for the alfalfa components of LEVEL 2 (Fig. 1) identifies the principle state variables (parts of the system) and rates (time-dependent processes) that control carbon flow (expressed as plant DM) in the system. The parts of the crop included in LEVEL 2 are identical to those in LEVEL 1. Materials available for top growth and storage (MATS) represent the pool of photosynthates after respiration has been accounted for. That material is partitioned into leaves (LEAF), stems (STEM), and total nonstructural carbohydrates (TNC) stored in the crown and taproot of the plant. The TNC material is used in the formation of basal buds (BUDS) that elongate into new leaves and stems during regrowth. The connecting arrows in Fig. 1 represent the material transfer involved in these processes.

Continued life of a plant depends upon the supply of either current photosynthates or accumulated TNC. Crop death is simulated in LEVEL 2 if simultaneously there is no input to MATS (i.e., no photosynthesis) and a TNC level less than 5 g m^{-2}. For photosynthesis to occur, there must be a supply of light and material present in either the LEAF or BUDS state variable.

Input into the MATS state variable approximates the net daily crop growth rate. Therefore, it is not necessary to calculate respiration rates associated with the use of recently formed photosynthates. However, not all of the alfalfa plant is accounted for in the simplified model representation (Fig. 1). The crown, taproot, and branch roots have been excluded. Consequently, the net daily crop growth rate overestimates growth in the parts of the plant included in LEVEL 2. To prevent an unrealistic accumulation of MATS, a rate variable for "other uses" of MATS is defined. The associated sinks (crown, taproot, and branch roots) are not explicitly defined or modeled, but growth of these sinks is accounted for.

A subtle difference between LEVEL 1 and LEVEL 2 is the inclusion of a respiration rate for TNC utilization ($\dot{R}$, Fig. 1). The crop growth rate data used in LEVEL 2 to account for net photosynthesis does not include a correction for the respiration associated with the utilization of TNC. Hence, this loss of carbon from TNC during the production of basal buds and regrowth must be computed. Quantitatively, the same correction was made in LEVEL 1, but the LEVEL 2 code was modified to make the process more obvious. In addition, TNC respiration of LEVEL 2 includes a maintenance component for overwinter use of TNC.

Radioactive labelling of alfalfa TNC has shown that the utilization pathway can be most accurately represented by transfers from TNC to the photosynthate pool called MATS in the model (Pearce et al., 1969; Smith and Marten, 1970). The model simplification is to channel the remobilized TNC through the same pathways as elongating buds, thus eliminating a rate equation. It was thought that this simplification might cause the errors in dry matter distribution noted as problems with LEVEL 1. That possibility was carefully investigated (Fick, 1977) and found not to be the case. Hence the same simplified TNC remobilization pathway is retained in LEVEL 2.

As noted above, the major deficiency of LEVEL 1 was a simultaneous overestimation of top growth and underestimation of TNC accumulation after

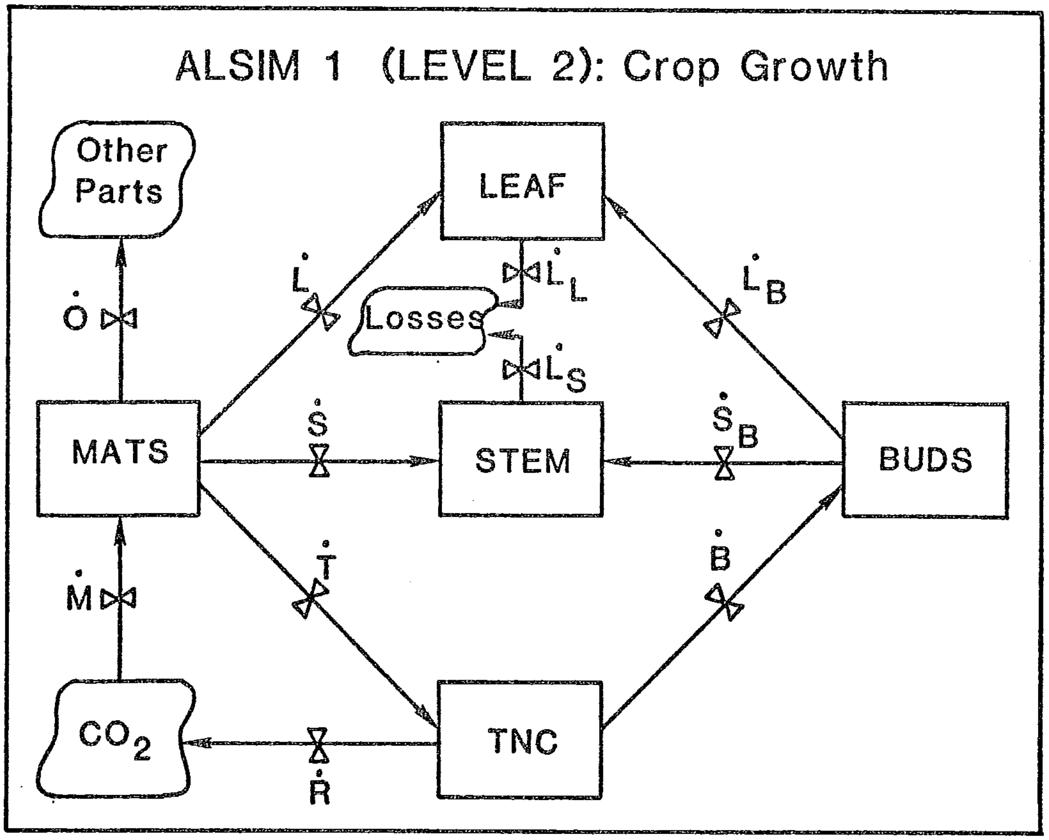


Figure 1. The relational diagram of the crop growth components of LEVEL 2 showing five main state variables and eleven processes to be simulated. The state variables represent parts of the simulated alfalfa crop: MATS (materials available for top growth and storage), LEAF (leaves), STEM (stems), TNC (total nonstructural carbohydrates in the taproots), and BUDS (basal buds for regrowth). The processes are described by rate equations that simulate the transfer of material between the parts of the crop: $\dot{M}$ (crop growth rate), $\dot{L}$ (leaf growth rate), $\dot{S}$ (stem growth rate), $\dot{T}$ (TNC storage rate), $\dot{R}$ (TNC respiration rate), $\dot{B}$ (bud growth rate), $\dot{S}_B$ (growth rate of stems coming from buds), $\dot{L}_B$ (growth rate of leaves coming from buds), $\dot{L}_L$ (rate of leaf loss), $\dot{L}_S$ (rate of stem loss), and $\dot{O}$ (rate of other uses of MATS).

the first simulated harvest of a growing season. In attempting to determine the cause of this problem, a conceptual error was uncovered in the LEVEL 1 computation of the maximum possible rate of TNC storage (PSTOR). It had been coded as a gross rate, but re-examination of the literature showed that the basic data were for a net rate. Adding the losses of TNC for respiration and bud growth to the PSTOR equation converted the net value to the intended gross value, but this change only partially corrected the TNC underestimation.

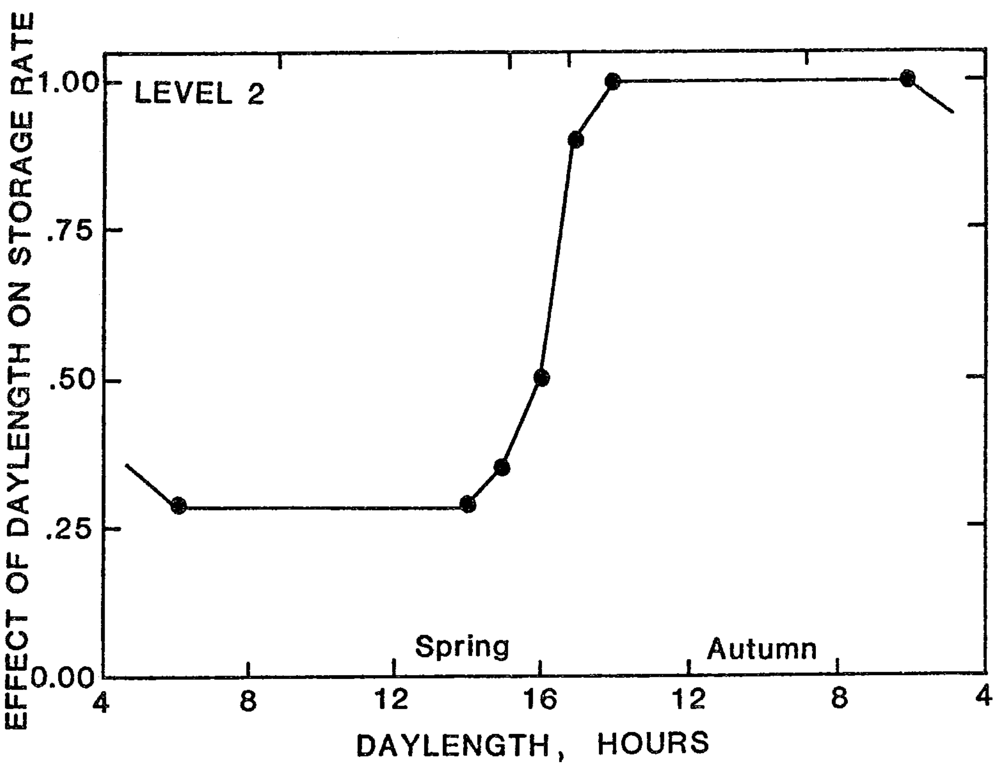


Figure 2. A new function in LEVEL 2 describing the effect of daylength on the rate of TNC storage in the taproots.

A further correction was made by adding the effect of daylength to the computation for the rate of TNC storage (Fig. 2). The original PSTOR equation included a maximum rate constant analagous to the equations for leaf and stem growth rate. The leaf and stem maximum growth rate constants, 0.2 and 0.499 g $m^{-2}day^{-1}$ respectively, were derived from Holt et al. (1975) and are retained in LEVEL 2. In LEVEL 1, the maximum growth rate constant for TNC was 1.8 g $m^{-2}day^{-1}$, and it was derived from Nelson and Smith (1968). It was determined, however, that that value applied to spring conditions and that summer and autumn rates of TNC storage could be much higher. In LEVEL 2, the maximum storage rate for TNC is increased to 3.5 g $m^{-2}day^{-1}$. It is then multiplied by a daylength factor that gives rates of about 1.0 g $m^{-2}day^{-1}$ with increasing daylengths but up to the maximum with decreasing daylengths (Fig. 2). A similar concept was used by Smith and Loewer (1981) in their forage growth model. The shape of the daylength function for LEVEL 2 was determined by sensitivity analyses which varied the spring rates from 1.0 to 2.0 and the autumn rates from 2.0 to 4.0 g $m^{-2}day^{-1}$. Trials were also conducted with altered rates of TNC utilization, but no improvement in model performance was obtained in that manner.

It was presumed that a major cause for overestimation of top growth rates in LEVEL 1 was failure to account for soil water deficiencies that commonly occur under nonirrigated conditions, even in the humid Northeast. Consequently, a soil water budget, with associated water-stress and crop-growth functions, was incorporated into the alfalfa model as the main change in developing LEVEL 2. The water budget model of Ritchie (1972) was directly incorporated, and the related energy budget computations of Ritchie (1974) were used to calculate total evapotranspiration. The principle state variable of this LEVEL 2 submodel is available water in the root zone (AW, Fig. 3), with inflow from precipitation and losses to evapotranspiration, runoff, and deep percolation. The model assumes a well-drained soil reaching field capacity within 1 day of the addition of excess water. Soil specific parameters required for use of the model are the available water at field capacity for the root zone (AWFC) and the available water fraction at which stress begins (AWFS), i.e., the fraction of AWFC remaining when growth processes are first affected. A water stress factor (WSF) is computed as AW/(AWFC·AWFS) and used directly as a reduction factor for the various elements of top growth rate when it has values of less than 1.0.

The water stress factor controlled the simulated production of top growth under conditions of limiting soil water supply. However, in some years on some soils limiting soil water supplies do not occur, and in those cases LEVEL 2 performed more poorly than LEVEL 1 in predicting second and third growths of alfalfa. This problem is explained in the following section, but it was reduced in importance by modifying the effect of daylength on the growth rates of leaves and stems (Fig. 4). It would be possible to make further improvements in model predictions by additional modification of those functions, but there are no physiological data known to the author to justify those changes and the original functions were taken from the literature (Holt et al., 1975).

The only other change of substance in developing LEVEL 2 was a slight modification in the function that describes bud elongation as a function of

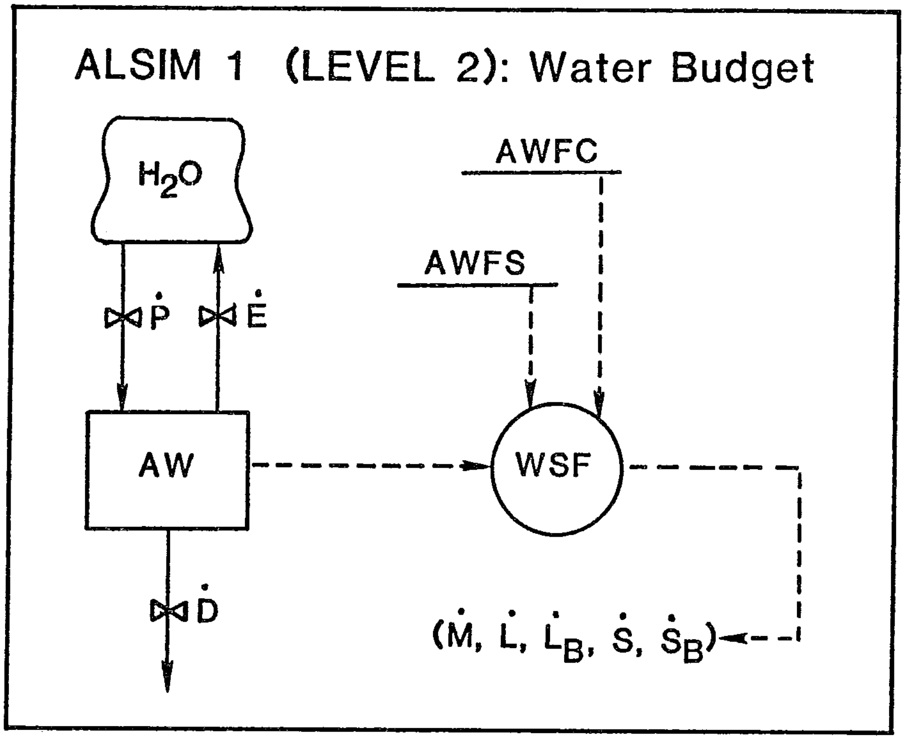


Figure 3. The relational diagram of the soil water budget component of LEVEL 2 showing the plant available water in the soil (AW) being increased by precipitation ($\dot{P}$) and decreased by evapotranspiration ($\dot{E}$) and runoff and deep percolation ($\dot{D}$). A water stress factor (WSF) is computed from AW and parameters for available water at field capacity (AWFC) and the available water fraction at which stress begins (AWFS). The growth rates $\dot{M}$, $\dot{L}$, $\dot{L}_B$, $\dot{S}$, and $\dot{S}_B$ (see Fig. 1) are influenced by WSF.

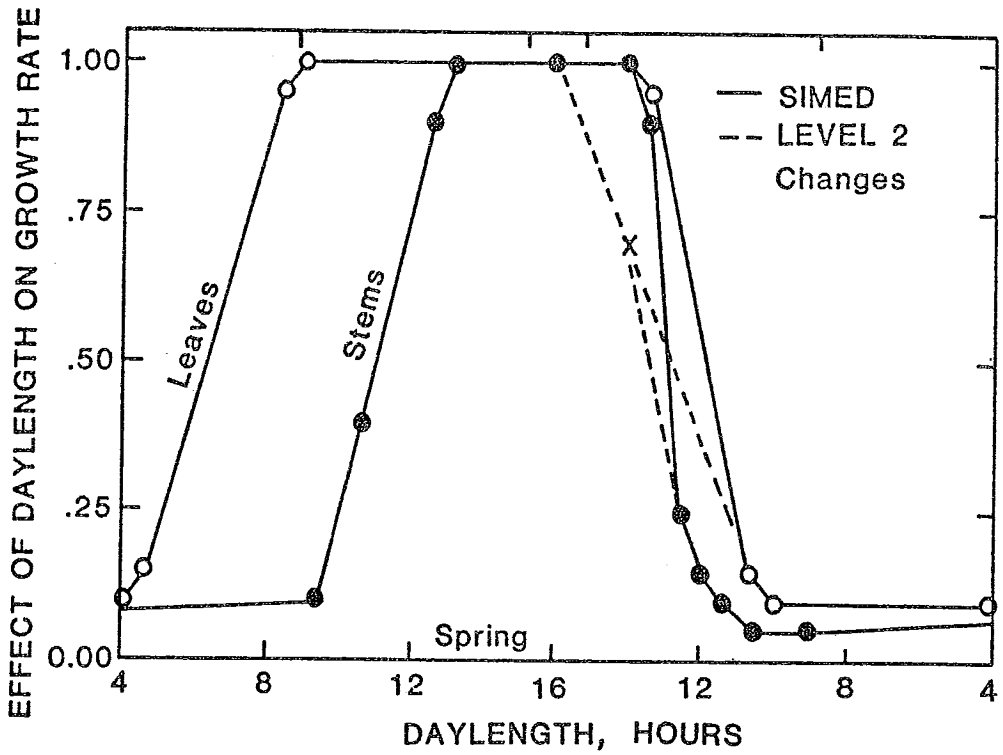


Figure 4. The functions describing the effect of daylength on growth rate of leaves and stems are identical to the SIMED and LEVEL 1 functions except for the decreasing daylengths as indicated by the dashed line for LEVEL 2.

daylength (BEFD). The transition from the rapid elongation to the non-elongating condition has been made somewhat less abrupt. All other changes in the LEVEL 2 code were made to improve readability and cause no change in model output.

The description of the dynamics of alfalfa growth represented by LEVEL 2 is not complete unless losses from the LEAF and STEM state variables are outlined. Losses due to harvesting, senescence, and freezing are included. Losses to insect defoliation can be simply added by incorporating the appropriate relationships into the leaf and bud state variable equations.

Harvesting losses account for herbage removal in a simulated cut. Senescence losses account for herbage death because of shading. Leaf yield in excess of a ceiling leaf yield is removed by senescence with a mean life of 7 days. The ceiling leaf area index set at 5 for long days ($\geq$15 hours of light) and 1.5 for short days ($\leq$12 hours of light). Those relationships were derived from Hunt et al. (1970) for alfalfa light interception. The same study provided the basis for computing the amount of solar radiation absorbed by the canopy which in turn established the rate of net canopy photosynthesis and crop growth rate. Herbage losses due to freezing are programmed to occur with a killing frost. The entire herbage canopy is lost when the mean air temperature drops below 2°C.

Several auxillary variables have been defined in LEVEL 2 for convenience in output interpretation. The total herbage is leaves plus stems and is called TOPS. The amount of hay in the last harvest (HAYHAR) and the total amount of hay harvested since the start of simulation (HAYTOT) are computed from the harvest rates of leaves and stems. The leaf area index (LAI) and the fraction of leaves in the herbage (FLEAF) and in the total harvested hay (FLHAY) are also available for output. The cumulated growing degree days with a 5°C base temperature (GDDB5) for any growth period and the cumulated days with water stress (DWS) for the growing season indicate important growth controlling factors for a particular simulated environment. The daylength (DAYLEN) can also be easily monitored in a given simulation run. The LEVEL 2 model has also been designed to conveniently allow multiple-year simulations.

Subsequent sections of this manual go into detail on the user options and input data requirements for LEVEL 2. Most of the physical and physiological constants and functions used in the model are not intended for modification by users. However, the sources for that information are given with the variable name definitions so that the sophisticated user can check original papers and assumptions and derive modified relationships, if desired.

MODEL PERFORMANCE

The LEVEL 2 model has been evaluated with regard to its performance in predicting water use, herbage growth, and TNC accumulation and utilization patterns. The predictions of water use by evapotranspiration were compared to measured rates and sums of pan evaporation for the 1974 growing season at Ithaca, NY. Gray et al. (1955) reported a ratio of evapotranspiration to pan evaporation for alfalfa at Ithaca of 1.0. Doss et al. (1964) reported a value of 1.05 for mature alfalfa in Alabama. The LEVEL 2 submodel predicted a ratio of 1.15 for the month of May and 1.03 for the entire growing season. The Ritchie soil water budget model used in LEVEL 2 thus appears to be well suited for alfalfa in New York State.

The patterns of top growth and TNC storage and utilization that are typical for alfalfa harvested three times in the growing season are presented in Fig. 5. The LEVEL 1 version deviated from the typical pattern by accumulating less TNC and producing more herbage (Fig. 6). When LEVEL 2 was used to simulate a fairly average year (1979 with 56 days in which soil water deficits reduced growth rates), the top growth and TNC patterns followed the expected trends (Fig. 7). The TNC yields predicted by LEVEL 2 were somewhat higher than the measured yields (Fig. 5), but field measurements were applied to only the upper 10 cm of taproot. Approximately 50% of the total TNC supply is present in that tissue (Escalada and Smith, 1972; Ueno and Smith, 1970), and so estimates of the total supply should exceed the measured TNC levels.

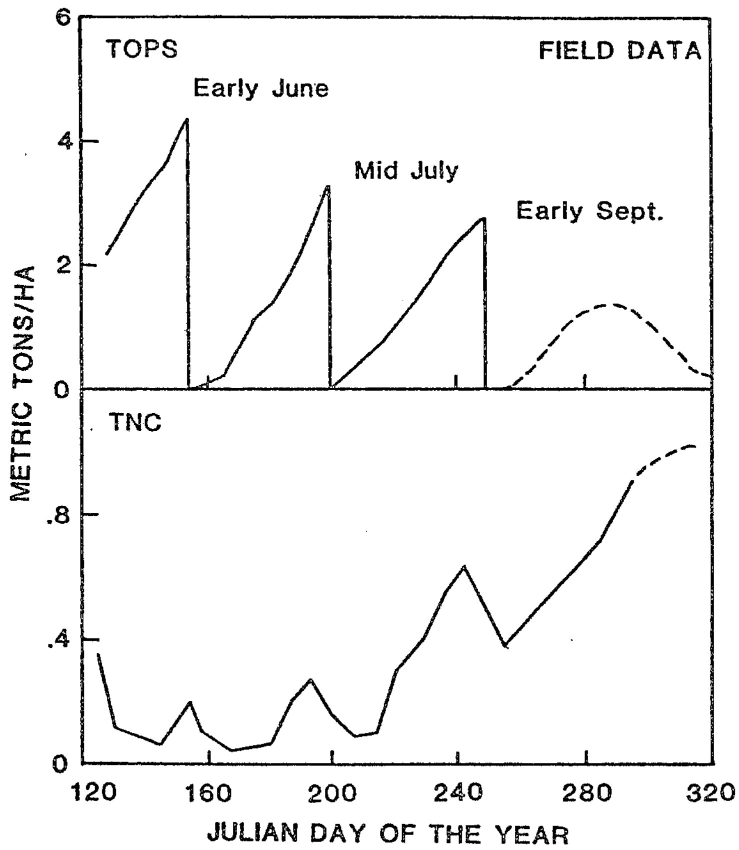


Figure 5. Typical field patterns for alfalfa herbage (TOPS) and root reserve (TNC) production and utilization. Measurements were made in 1972. The TNC yields represent about 50% of the total amount of TNC present.

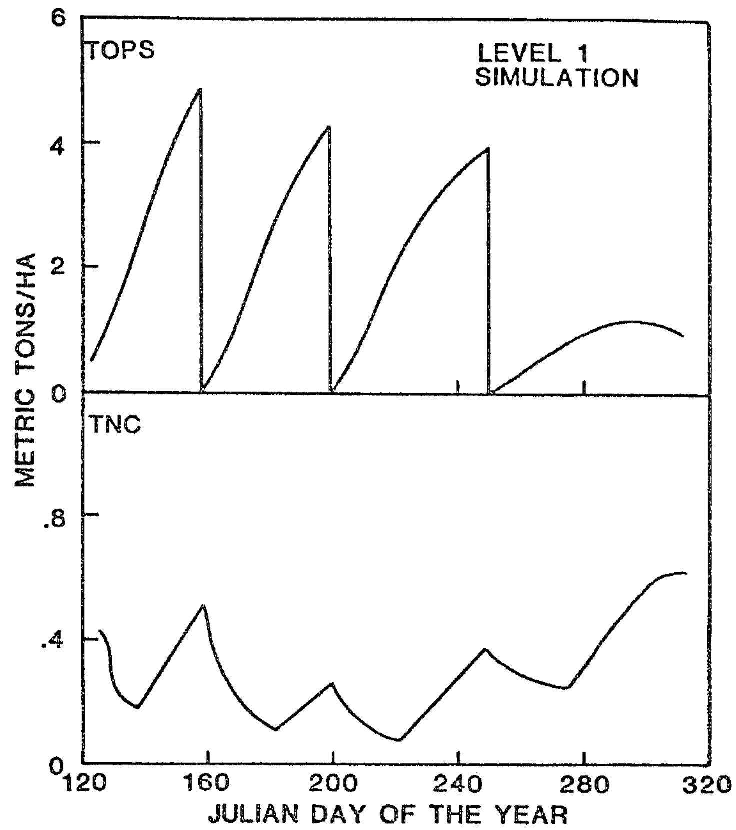


Figure 6. Simulated herbage (TOPS) and root reserve (TNC) production and utilization patterns for 1972 using the LEVEL 1 model.

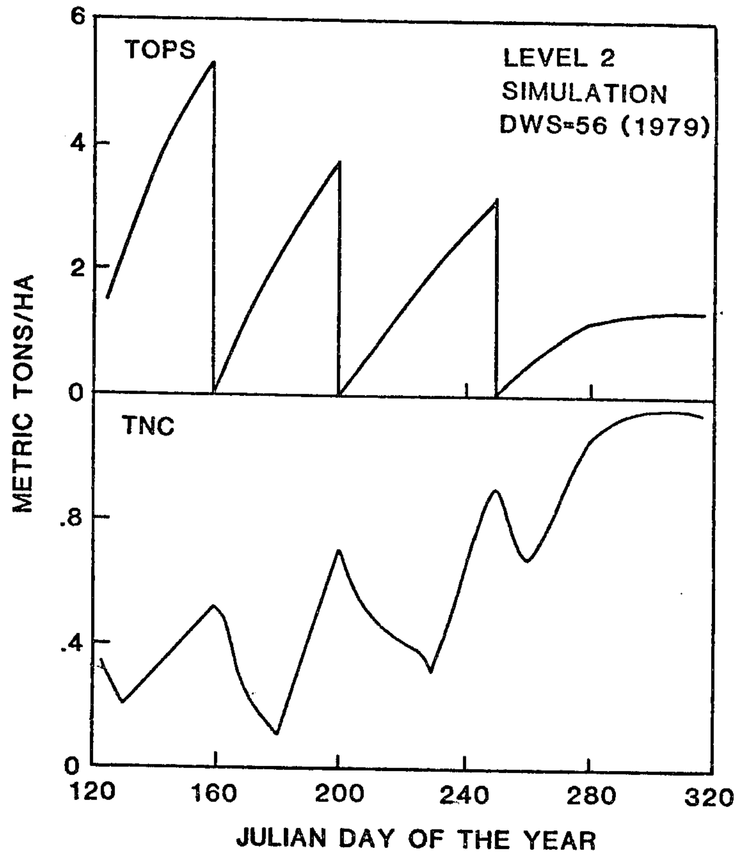


Figure 7. Simulated herbage (TOPS) and root reserve (TNC) production and utilization patterns for 1979 using the LEVEL 2 model. The soil water supply in 1979 was about average resulting in 56 days in the growing season with some stress.

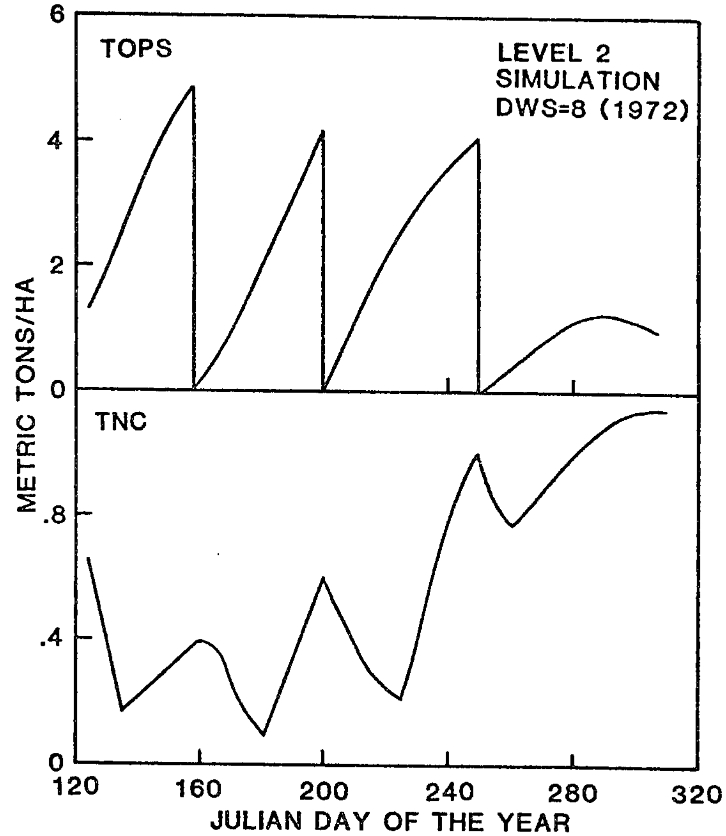


Figure 8. Simulated herbage (TOPS) and root reserve (TNC) production and utilization patterns for 1972 using the LEVEL 2 model. The soil water supply in 1972 was much more favorable than average resulting in only eight days in the growing season with some stress.

Obvious deviations between LEVEL 2 predictions and field observations occurred when the model was used to simulate a year with very little water stress (Fig. 8). The TNC patterns remain reasonable, but the expected ratio of 7:5:3 in the herbage yields for first, second, and third cuts is not followed. Before the function controlling the effect of daylength on growth rate was modified (Fig. 4), the third harvest was even higher. The problem comes from the fact that LEVEL 2 in general predicts higher TNC levels during the second and third growth than did LEVEL 1. The physiological theory incorporated into the models gives faster regrowth with higher TNC levels, and so the top growth pattern for the third harvest of LEVEL 2 is even more in error than that for LEVEL 1 when there is no water stress.

It would be possible to force LEVEL 2 to reduce late season growth rates by further modification of the daylength function (Fig. 4). This would allow even more TNC accumulation and unrealistically interfere with TNC utilization. At this stage, we know of no mechanistic data to justify such a change. The high estimates of third growth alfalfa do not interfere with model use in the alfalfa weevil program, since the pest attacks mainly the first and second growth in the Northeast (Fick and Liu, 1976). If more accurate yield predictors are needed for the third harvest, other options are available (Fick and Onstad, 1982).

One further comparison of LEVEL 1 and LEVEL 2 TNC patterns was made by simulating cutting managements with 2, 3, 4, and 10 harvests for average weather conditions at Ithaca (Fig. 9 and 10). The LEVEL 2 patterns were more realistic, showing the expected general increases in TNC levels even at 4 cuts. With 10 simulated harvests, LEVEL 2 predicted stand death while LEVEL 1 predicted survival with very low yields of TNC.

Statistical evaluations of LEVEL 1 and LEVEL 2 were made by simulating the cutting management experiments of Sumberg (1977). The field trials were run over two years across three soils and three cutting managements giving a total of 60 harvests for comparison with model predictions of herbage yield. On the most productive soil site where LEVEL 1 would be expected to be most accurate, the regression equation was

$$Y = -2.350 + 1.381X, \quad r^2 = 0.94, \quad n = 20, \quad SEy = 0.35$$

where Y was the field data and X the model prediction. The coefficient of determination (r^2) was very high, but the intercept and slope parameters deviate considerably from the respective 0.0 and 1.0 values of an ideal model.

When LEVEL 1 was applied to the whole data set (Fig. 11) the resulting equation was

$$Y = -2.436 + 1.255X, \quad r^2 = 0.73, \quad n = 60, \quad SEy = 0.72$$

In this case, the model was not expected to perform as well because of the importance of soil water supply as a limiting factor on the additional soils included in the analysis.

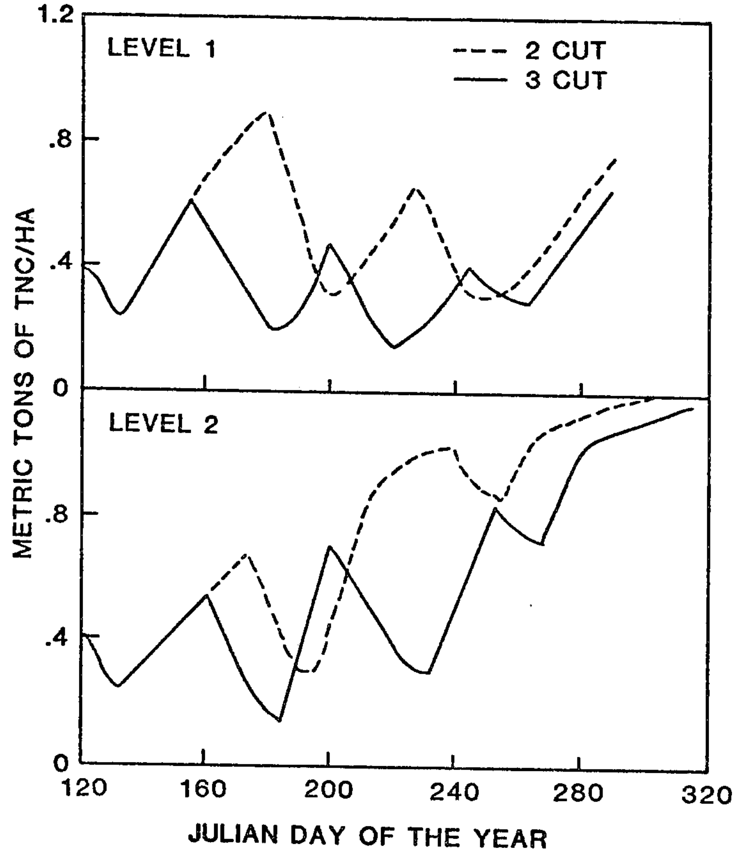


Figure 9. Comparison of the TNC patterns predicted by the LEVEL 1 and LEVEL 2 models with 2 and 3 harvests during the growing season.

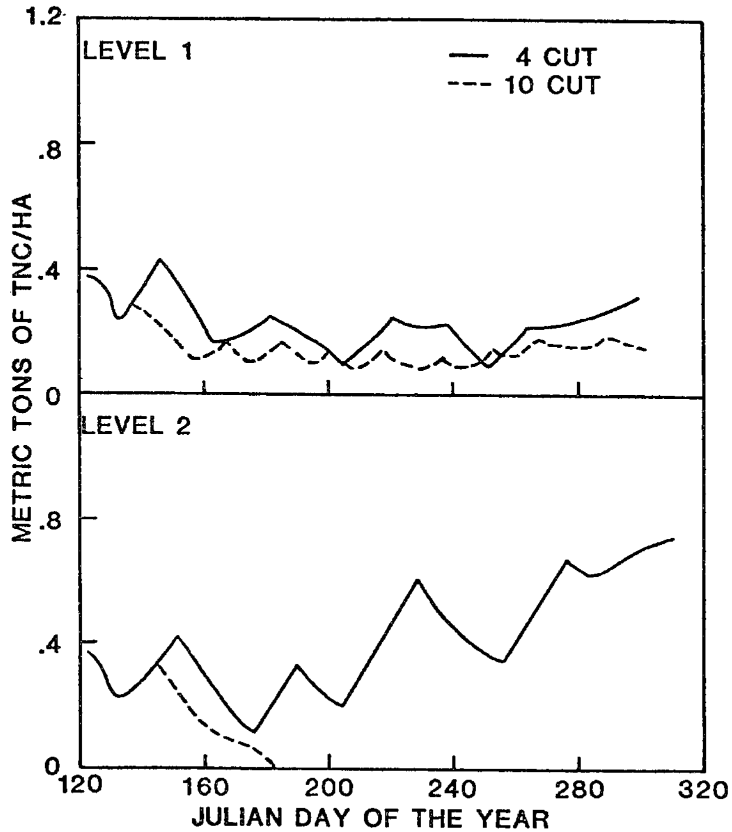


Figure 10. Comparison of the TNC patterns predicted by the LEVEL 1 and LEVEL 2 models with 4 and 10 harvests during the growing season.

When LEVEL 2 was applied to the entire data set (Fig. 12), the regression equation was

$$Y = -0.521 + 0.908X,\ r^2 = 0.69,\ n = 60,\ SEy = 0.77$$

The slope and the intercept are greatly improved and no longer significantly different than 1.0 and 0.0, respectively. However, the standard error of the estimate and the coefficient of determination are slightly poorer than for LEVEL 1 on the same data set. One of the years in the data set (1975) was a year with near optimal rainfall patterns. The yield overestimate of LEVEL 2 in the third harvest under such conditions accounted for its relatively poor showing. When applied to only the other year (1974), LEVEL 2 slightly, though not significantly, outperformed LEVEL 1.

In summary, LEVEL 2 is a more accurate predictor of TNC patterns than is LEVEL 1. In general, it gives accurate predictions of top yields; however, LEVEL 2 predictions of late season yields are less accurate than those of LEVEL 1 in the event that there is little or no growth limitation from soil water shortages.

ASSUMPTIONS AND LIMITATIONS

The LEVEL 2 model was developed to simulate alfalfa production under recommended conditions in the zone around the Great Lakes. Well-drained soils without significant fertility limitations are assumed. In this region, both excess and deficient soil water supplies interfere with alfalfa production. Soil water deficiencies are simulated, but LEVEL 2 does not describe the effect of poor drainage and excess water. Attempts are being made to model the effects of poor drainage (Thompson and Fick, 1980), and future models may describe those factors.

The model also assumes essentially pure stands of alfalfa (greater than 90% of the botanical composition) at the peak of their vigor and productive potential. Thus, LEVEL 2 overestimates production levels achieved by farmers over the life of the stand, but it should approximate yields from their best stands in any given year.

In the production zone of interest, alfalfa is generally harvested two to four times during the growing season and no more frequently than every 35 days. Simulations of more intensive managements have not been run, with the exception of the 10-cut simulation mentioned earlier that predicted stand death. It appears that LEVEL 2 will overestimate the size of the third and fourth harvest of a conventional system by 10 to 30% in those years or on those soils without late-season soil water limitations.

Two important assumptions are associated with the fact that the model was designed for the zone around the Great Lakes. In the first place, the basic growth rate computations depend on leaf area and light absorption relationships measured in Ontario, Canada at 43.5°N Lat. Model performance may deteriorate at latitudes that differ by more than 5° from that center because predicted canopy light relations will be in error. In the second place, it is assumed that winter temperatures will drop below the killing

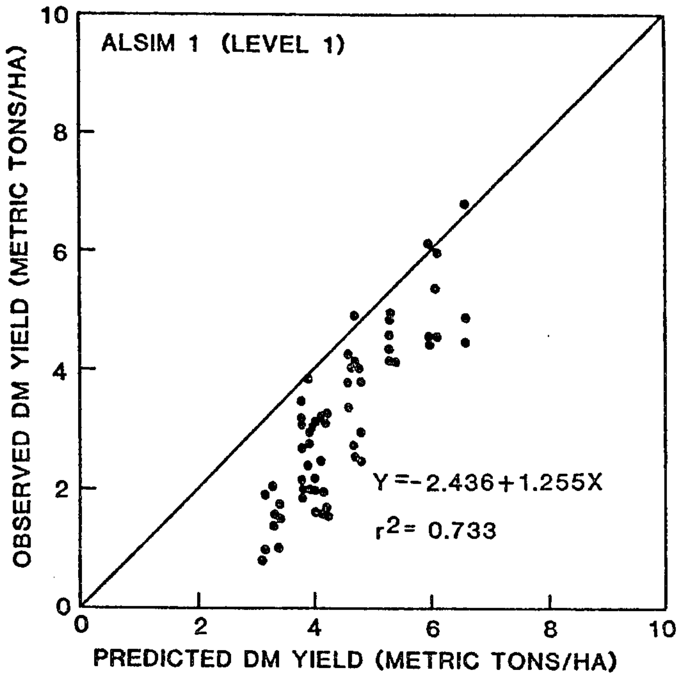


Figure 11. Relationship between predicted alfalfa yields using the LEVEL 1 model and actual field observations made in 60 harvests in 1974 and 1975.

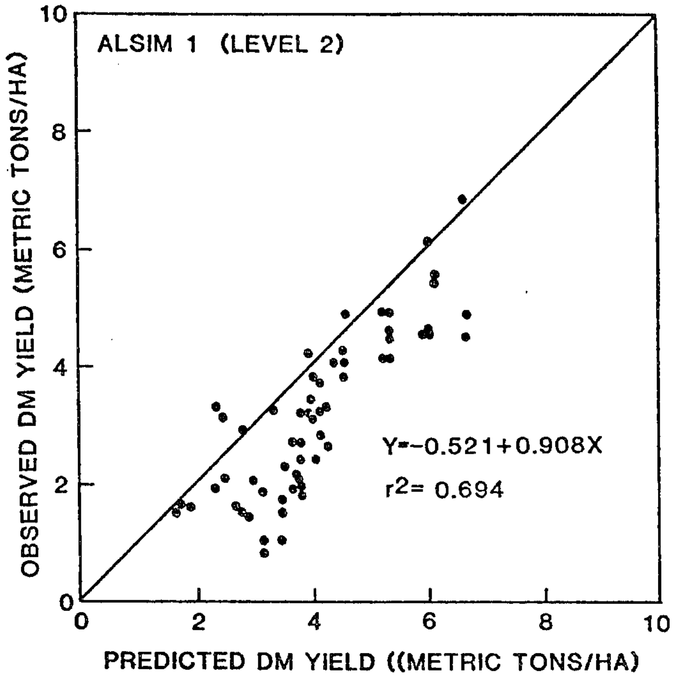


Figure 12. Relationship between predicted alfalfa yields using the LEVEL 2 model and actual field observations made in 60 harvests in 1974 and 1975.

frost level (2°C mean air temperature). A killing frost is used to reset the growing degree day counter. Without a reset, stand maturity in the spring will be in error for simulations that include a prior winter period.

The daylength counter keeps track of the direction of daylength change, and if simulations are initiated when the daylength is decreasing, the direction of change will be in error for the first simulated day. However, that error should be fairly small if initial leaf areas are zero. Further details on assumptions related to run initialization can be found in the section on use of the model.

The internal physiological functions, constants, and parameters have been drawn from the literature in as far as possible. The sources of the physiological data used in the model are given with the definition of terms. In a number of cases, published data could not be found, and values were determined by going directly to the field or by using sensitivity analysis to select a magnitude giving reasonable output.

DEFINITION OF TERMS

This section is divided into two parts with the definition of variable names used for input data preceding those used for other variables. In CSMP the special labels PARAMETER, INCON, CONSTANT, TABLE, and FUNCTION identify the information that follows as data. Data entered in this way must be given a variable name. This allows the data to be changed between runs without changing the structure of the model. A TABLE contains subscripted data; a FUNCTION contains sets of x,y-coordinates.

The dimensions of the yield variables in the following definitions are grams of dry matter per square meter of ground surface area. Water is measured in millimeters.

Input Variable Names (data)

ALCROP Albedo of the closed crop canopy as a dimensionless fraction.

ALPHA Coefficient of soil evaporation from Ritchie (1972), in mm day$^{-1/2}$.

ALSOIL Average albedo of bare soil as a dimensionless fraction.

AWFC Available water in the soil root zone at field capacity, in mm.

AWFS The fraction of AWFC at the onset of stress as a dimensionless fraction (Lucey and Tesar, 1965).

AWI Initial available soil water in the root zone, in mm.

BEFD Dimensionless fraction of potential bud elongation rate as a function of daylength, in hours. No references found.

BEFSR Dimensionless fraction of potential bud elongation rate as a function of solar radiation not absorbed by the leaf canopy, in langleys (ly) day^{-1}. No references found.

BEFT Dimensionless fraction of potential bud elongation rate as a function of average air temperature, in degrees Celsius. No references found.

BUDCF Ceiling on yield of buds, in g m^{-2}, as a function of TNC yield, in g m^{-2}. No references found.

BUDI Yield of buds at the start of simulation, in g m^{-2}.

CDAY Julian days of the year on which cuts are made.

CSF Ceiling on fraction of stems in the TOPS (Fick, 1972 unpublished data).

DELT Simulation time-step size, in days.

DTL Mean life of the decay time of senescing leaves, in days. No references found.

DTS Mean life of the decay time of senescing stems, in days. No references found.

EDLG Dimensionless fraction of potential leaf growth rate as a function of daylength, in hours (Holt et al., 1975).

EDS Dimensionless fraction of potential TNC storage rate as a function of daylength, in hours. No references found.

EDSG Dimensionless fraction of potential stem growth rate as a function of daylength, in hours (Holt et al., 1975).

ELLG Dimensionless fraction of potential leaf growth rate as a function of leaf yield, in g m^{-2} (Holt et al., 1975).

ESPM Dimensionless fraction of potential crop growth rate as a function of maturity, in growing degree days (Holt et al., 1975).

ESSG Dimensionless fraction of potential stem growth rate as a function of stem yield, in g m^{-2} (Holt et al., 1975).

ETG Dimensionless fraction of potential growth rate as a function of average air temperature, in degrees Celsius (Gist and Mott, 1957; Heinrichs and Nielsen, 1966).

ETNCS Dimensionless fraction of potential TNC storage rate as a function of TNC yield, in g m^{-2} (Nelson and Smith, 1968).

FTGLF Dimensionless fraction of top growth in leaves as a function of leaf yield, in g m^{-2} (Fick, unpublished 1973 data).

GDDB5I Growing degree days with a 5°C base for the top growth present at the start of simulation.

GFASR Potential growth rate, in g m^{-2} day^{-1}, as a function of absorbed solar radiation, in ly day^{-1} (Black, 1963).

HLEAFI Yield of harvested leaves at the start of simulation, in g m^{-2}.

HSTEMI Yield of harvested stems at the start of simulation, in g m^{-2}.

KFROST Killing frost temperature, in degrees Celsius.

L Latent heat of vaporization, in ly mm^{-1}.

LAT Latitude of the study location, in decimal degrees.

LDABT With long days (≥15 hours), the dimensionless fraction of solar radiation absorbed by leaves, in ly day^{-1}, as a function of LAI (Hunt et al., 1970).

LDCLAI Leaf area index giving 95% absorption of solar radiation on long days, from LDABT.

LEAFI Yield of leaves at the start of simulation, in g m^{-2}.

MATSI Yield of materials available for top growth and storage at the start of simulation, in g m^{-2}.

MAXTF Maximum temperature of the air, in degrees Fahrenheit, as a function of day of the year.

Mean Life With exponential decay, the time of decrease to 1/e or 0.368 of the original amount. Mean life instead of half-life is used in coding because of the simplicity of the form: size change during time interval = present size/mean life.

MINTF Minimum temperature of air, in degrees Fahrenheit, as a function of day or the year.

MLBUDS Mean life of bud disappearance, in days (Leach, 1968).

MLOSC Maintenance loss constant for overwinter respiration of TNC as a fraction per day (Jung and Smith, 1960).

MLTNC Mean life of TNC disappearance, in days (Smith and Silva, 1969).

PPTF Precipitation rate as a function of day of the year, in mm day^{-1}.

PTF Priestley-Taylor factor (Ritchie, 1974).

RCTNC Fraction of TNC lost to respiration when buds are formed or regrowth occurs (Smith and Marten, 1970).

RGR Relative growth rate of plant material, in g g^{-1} (de Wit and Goudriaan, 1978).

SDABT With short days ($\leq$12 hours), the fraction of solar radiation absorbed by leaves, in ly day^{-1}, as a function of LAI (Hunt et al., 1970).

SDCLAI Leaf area index giving 90% absorption of solar radiation on short days, from SDABT.

SLA Specific leaf area, in m^2 g^{-1} (Holt et al., 1975; Fick and Holthausen, 1975).

SRADF Solar radiation, in ly day^{-1}, as a function of Julian day of the year.

STEMI Yield of stems at the start of simulation, in g m^{-2}.

TNCI Yield of TNC at the start of simulation, in g m^{-2}.

U Upper limit of cumulative evaporation from soil during stage one drying varying from 5 to 15 mm depending upon soil hydraulic properties (Ritchie, 1972).

YEAR Calendar year in which simulation begins.

Output Variable Names

ALBEDO Fraction of incoming solar radiation reflected from the crop surface.

AVTA Average temperature of the air, in degrees Celsius.

AW Available soil water supply in the root zone, measured in mm.

BEF Bud elongation factor integrating environmental effects on elongation rate.

BUDC Ceiling yield of basal buds, in g m^{-2}.

BUDS Yield of basal buds, in g m^{-2}.

CCOND Crop condition based on TNC supply and current net photosynthesis.

CLEAF Ceiling yield of living leaves, in g m^{-2}.

COSUNR Cosine of the hour of sunrise, in radians.

CSTEM Ceiling yield of living stems, in g m^{-2}.

CUT Signal for simulating a harvest.

DAYLEN	Daylength in hours with a positive sign when daylengths are increasing and a negative sign when they are decreasing.
DAYLEN	Daylength in hours. This number is always positive, and it is calculated with the method of McKinion et al. (1975).
DD	Daily increment in GDDB5.
DDF	Signal to reset GDDB5 to zero when there is a killing frost.
DDR	Signal to set GDDB5 to zero when there is a cut.
DEATH	Value of CCOND when the crop will die.
DECR	Declination of the sun, in radians.
DECY	Delination of the sun for yesterday, in radians.
DG	"Delta-gamma" ratio for calculating EO (Penman, 1948; Ritchie, 1974).
DLFAC	Daylength factor, the fraction of the difference between a short day ($\leq$12 hours) and a long day ($\geq$15 hours).
DRAIN	Drainage from the soil by runoff and deep percolation, in mm day^{-1}.
DTGR	Daily total growth rate, in g $m^{-2}day^{-1}$.
DWS	Number of days with water stress since the start of simulation.
EMIS	Emissivity of the sky (Ritchie, 1974).
EO	Potential evapotranspiration, in mm day^{-1}.
EP	Plant evaporation rate or transpiration, in mm day^{-1}.
ES	Soil evaporation rate, in mm day^{-1}.
ESO	Potential evaporation rate from the soil surface, in mm day^{-1}.
ESR	Evaporation from the soil, in mm day^{-1} (Ritchie, 1972).
ESX	Evaporation rate from the soil surface during stage 2 evaporation, in mm day^{-1} (Ritchie, 1972).
ET	Total evaporation rate from plants and soil, in mm day^{-1}.
FLEAF	Fraction of leaves in tops.
FLHAY	Fraction of leaves in the harvested hay.

FPS	Fraction of possible sunshine on a given day.
FRL	Loss of leaves to freezing, in g $m^{-2}day^{-1}$.
FRS	Loss of stems to freezing, in g $m^{-2}day^{-1}$.
FSRADA	Fraction of solar radiation absorbed by the crop canopy.
FTGL	Fraction of top growth in leaves.
GDDB5	Growing-degree days with a base temperature of 5°C.
GRB	Growth rate of buds, in g $m^{-2}day^{-1}$.
GRL	Growth rate of leaves, in g $m^{-2}day^{-1}$.
GRLB	Growth rate of leaves coming from bud elongation, in g $m^{-2}day^{-1}$.
GRM	Potential rate of top growth and storage, in g $m^{-2}day^{-1}$.
GRS	Growth rate of stems, in g $m^{-2}day^{-1}$.
GRSB	Growth rate of stems coming from bud elongation, in g $m^{-2}day^{-1}$.
HA	Mean hour angle of the sun, in radians.
HAYHAR	Hay harvested in the last simulated cut, in g m^{-2}.
HAYTOT	Hay harvested since the start of simulation, in g m^{-2}.
HLEAF	Harvested leaves since the start of simulation, in g m^{-2}.
HRL	Loss of leaves to harvesting, in g $m^{-2}day^{-1}$.
HRS	Loss of stems to harvesting, in g $m^{-2}day^{-1}$.
HSTEM	Harvested stems since the start of simulation, in g m^{-2}.
IRRIG	Irrigation rate, in mm day^{-1}.
LAI	Leaf area index, in m^2 m^{-2}.
LATR	Latitude of the experimental location, in radians.
LDAB	Long-day solar radiation absorption as a fraction of the total incoming solar radiation.
LEAF	Yield of leaves, in g m^{-2}.
LOSSL	Total leaf losses, in g $m^{-2}day^{-1}$.
LOSSS	Total stem losses, in g $m^{-2}day^{-1}$.

MATS	Materials available for top growth and storage, in g m^{-2}.
MAXT	Maximum daily air temperature, in degrees Celsius.
MINT	Minimum daily air temperature, in degrees Celsius.
MLOSS	Maintenance respiration loss of TNC, in g $m^{-2}day^{-1}$.
NCUT	Number of cuts to be simulated.
NRAD	Net radiation, in ly day^{-1}.
NRADS	Net radiation at the soil surface, in ly day^{-1}.
OUM	Other uses of MATS, in g $m^{-2}day^{-1}$.
P	Combination of rainfall and irrigation rate, in mm day^{-1}.
PGRL	Potential growth rate of leaves, in g $m^{-2}day^{-1}$.
PGRS	Potential growth rate of stems, in g $m^{-2}day^{-1}$.
PPT	Precipitation rate, in mm day^{-1}.
PSTOR	Potential rate of TNC storage or accumulation, in g $m^{-2}day^{-1}$.
PTFS	Empirical Priestley-Taylor factor for soil evaporation (Ritchie, 1972).
SDAB	Short-day solar radiation absorption as a fraction of the total incoming solar radiation.
SRAD	Solar radiation, in langleys (ly) day^{-1}.
SRADA	Solar radiation absorbed by the crop canopy, in ly day^{-1}.
SRADM	Solar radiation maximum with clear skies, in ly day^{-1}.
SRADN	Solar radiation not absorbed by the crop canopy, in ly day^{-1}.
SRL	Loss of leaves to senescence, in g $m^{-2}day^{-1}$.
SRS	Loss of stems to senescence, in g $m^{-2}day^{-1}$.
STEM	Yield of stems, in g m^{-2}.
STOR	Rate of TNC storage or accumulation, in g $m^{-2}day^{-1}$.
SUMS1	Cumulative evaporation from soil surface during stage one evaporation, in mm (Ritchie, 1972).
SUMS2	Cumulative evaporation from soil surface during stage 2 evaporation, in mm (Ritchie, 1972).

SUN	Solar radiation at the top of the atmosphere, in ly day^{-1}.
SUNRIZ	Time from sunrise until solar noon, in radians.
T	Time since the start of stage 2 drying, in days.
TIME	Julian day of the year.
TNC	Yield of total nonstructural carbohydrates, in g m^{-2}.
TNCD	TNC yield when death occurs, in g m^{-2}.
TNCM	Maximum yield of TNC reached since the start of simulation, in g m^{-2}.
TNCS	Yield of TNC reflecting the size of the overwintering plant to be maintained, in g m^{-2}.
TOPS	Yield of the harvestable herbage, in g m^{-2}.
TRAD	Net thermal radiation of the earth's surface, in ly day^{-1}.
TRESP	TNC respiration rate, in g $m^{-2} day^{-1}$.
WSF	Water stress factor as a dimensionless fraction.
YDAYL	Yesterday's daylength, in hours.

USE OF THE MODEL

Language, Program, and Computer Characteristics

The LEVEL 2 model is written in the application-oriented computer language CSMP III (Speckhart and Green, 1976). The CSMP language is based on FORTRAN IV (LEVEL G1) and because of this, FORTRAN IV code can be included in the CSMP source program, and translations of the entire source program into FORTRAN IV are reasonably straight forward. As an example, within LEVEL 2 the computation of soil evaporation rate (ESR) is coded entirely in FORTRAN.

For those purposes where a FORTRAN IV version of LEVEL 2 is needed, the text by Speckhart and Green (1976) provides a useful explanation of the CSMP library functions. All the primary state variables of LEVEL 2 are computed using the CSMP-INTGRL function and rectangular integration. Mathematically, the INTGRL function for state variables is represented as follows:

$$V_{t+\Delta t} = V_t + \dot{V}_t \cdot \Delta t$$

where t = time

V = yield of state variable V

$\dot{V}$ = rate of change in V

Δt = integration time-step size.

The CSMP language is largely a set of library functions of which the INTGRL function just described is representative. Translation of LEVEL 2 into FORTRAN IV requires an understanding of the operations performed by those library functions. In addition to the CSMP III library, the FORTRAN IV (LEVEL G1) library is also available to the system. A FORTRAN IV "update subroutine" is a standard part of the output, and it can be used to sequence statements in a translated version. An example of a FORTRAN IV version of LEVEL 2 has been prepared by Onstad and Fick (1981).

The program was written in modular fashion both to facilitate ease of reading and ease of code verification. Model data for each section forms the final part of the particular module. The sequence of sections is as follows:

1. Initial section: input run-specific data and calculate run-specific initial conditions.
2. Cutting management section.
3. Crop weather section.
4. Evapotranspiration section.
5. MATS section.
6. LEAF section.
7. STEM section.
8. TNC section.
9. BUD section.
10. Crop death section: terminates run if the crop dies.
11. Terminal section: computes initial conditions for a subsequent year of simulation.
12. Run control section: input time variables and specify output and output format.

The program requires a minimum of 102 K bytes of storage and is normally run in the 120 K region on the IBM 370/168 computer. In general, it has taken 5 to 6 seconds of central processor time (CPU) to simulate a growing season and generate 1000 to 2000 lines of printed output. Graphical output requires 8 to 10 seconds of CPU for a similar job.

Input Data

To run a simulation with LEVEL 2, the following run-specific data must be supplied to the initial section:

LAT — The latitude of the location for which alfalfa growth is to be simulated, in decimal degrees.

YEAR The initial calendar year of the simulated trial.

GDDB5I The growing degree days with a 5°C base temperature that have been received by the top growth present at the start of simulation.

AWI The initial available water supply in the root zone, in mm.

AWFC The soil parameter specifying available water at field capacity in the root zone, in mm.

LEAFI The initial yield of leaves, in g m^{-2}.

STEMI The initial yield of stems, in g m^{-2}.

TNCI The initial yield of TNC, in g m^{-2}.

BUDI The initial yield of basal buds, in g m^{-2}.

MATSI The initial yield of MATS, in g m^{-2}.

Specification of the above crop parameters requires field measurement of the appropriate plant fractions and some knowledge of previous growing conditions. However, if a run is started after a killing frost in the autumn or before growth begins in the spring, the following variables should have zero initial values: GDDB5I, LEAFI, STEMI, MATSI. Typical levels for TNCI and BUDI at those times are 100 and 10, respectively. At that stage AWI will generally equal AWFC. The value of AWFC can be found in soil survey publications for the soil series being simulated.

The cutting management section requires that the number of harvests to be made in a growing season be specified on a STORAGE card and that the Julian dates for the harvests be entered in a TABLE. The variable name associated with cutting dates is CDAY, and examples of correct data specification is included in the comment cards in the initial section.

The sample listing of LEVEL 2 presented in this manual uses standard weather station data as input. The data is input as x, y-coordinates in FUNCTION statements under the following definitions:

MAXTF The maximum daily air temperature function, in degrees Fahrenheit.

MINTF The minimum daily air temperature function, in degrees Fahrenheit.

SRADF The solar radiation function, in ly day^{-1}.

PPTF The precipitation function, in mm day^{-1}.

The data strings are for mean monthly observations at Ithaca, NY in 1979 and 1980. The x-coordinate is the Julian date, and the y-coordinate is the weather parameter. The data is input to the program with the AFGEN library function which uses linear interpolation to compute the weather for a given day from the monthly means.

If the user wishes to use LEVEL 2 without altering structural statements, weather data should be input in the units, under the variable names, and in the format illustrated in the listing. It is possible to use actual daily observations instead of monthly means in that format. The monthly means were used in this manual simply for the sake of illustration. It should be noted that the version with monthly mean data generates a rainfall event (PPT) every seven days. This was done to maximize the efficiency of water use in the evapotranspiration section. However, using real weather data requires that the PPT equation be changed to

PPT = AFGEN (PPTF, TIME)

The user can also alter the way in which weather data is input. What is required by the computations within LEVEL 2 are the following:

AVTA The mean daily air temperature, in degrees Celsius.

PPT The amount of precipitation, in mm day^{-1}.

SRAD The solar radiation, in ly day^{-1}.

The equations for MAXT, MINT, SRAD, and PPT at the front of the weather section can be rewritten to accept data with different units, formats, and variable names as desired.

<u>Output</u>

Essentially any variable of the model defined in the list of output variable definitions can be requested as output under either the PRINT or OUTPUT commands. Speckhart and Green (1976) detail the requirements of using these commands in CSMP III. In general the PRINT command gives printed output and the OUTPUT command gives both graphical and printed output.

Commonly specified output variables are:

TOPS The yield of harvestable herbage, in g m^{-2}.

TNC The yield of TNC, in g m^{-2}.

HAYHAR The yield of hay harvested in the last simulated harvest, in g m^{-2}.

HAYTOT The yield of hay harvested since the start of this simulation run, in g m^{-2}.

FLEAF The fraction of leaves in TOPS.

FLHAY The fraction of leaves in HAYTOT.

Output is controlled from the run control section.

Run Control

The cards of the run control section specify the timing characteristics and output presentations of a simulation run. The TIMER card should have the following format:

TIMER DELT = 1., TIME = 90., FINTIM = 300., PRDEL = 1., OUTDEL = 7.

The integration time-step size (DELT) should always be set to 1. The other parameters can be varied. TIME specifies the initial Julian day of simulation (90. = March 30). FINTIM specifies the last day of simulation (300. = October 27). The variables PRDEL and OUTDEL control the time interval between printed and plotted output variables respectively. As mentioned earlier, all time variables are in days.

Variables desired as printed output are listed on a PRINT card. A TITLE card labels the printed output. Variables to be printed and plotted are listed on an OUTPUT card with up to five variables per card. A LABEL card labels the graphical output.

An END card specifies the end of a run-control data set for a particular case. The example listing shows how a multiple-year run is controlled with the END card. The FINTIM is set to 365. (December 31) for the first year. Following the END card, the weather data for the next year (1980) is input along with new TIMER, TITLE, and END cards. The TIME on the new TIMER card is set to 1. (January 1) for a continuation of the simulation. The TERMINAL section of the model computes initial conditions for the new year if the run is continued. It should be noted that these computations will be accurate only if the first year is terminated on December 31. It is possible, for example, to terminate the first year on day 300 and start the next on day 90, but in that case the computations of the TERMINAL section might not be accurate.

PROGRAM LISTING AND EXAMPLE RUN

The following example of a simulation run with LEVEL 2 was set up for Ithaca, NY (42.7° N latitude), starting on day 65 (March 6) of 1979 and running through day 281 (October 7) of 1980. A Niagara silt loam soil with 145 mm of available water at field capacity for the root zone was modeled. At that relatively early initial date, state variables were initialized at zero, except for TNCI and BUDI which were set at 100 and 10 g m^{-2}, respectively. The simulated harvest dates in both growing seasons were 157, 200, and 250. The corresponding calendar dates are June 6, July 19, and September 7 in 1979. In 1980, the calendar dates are one day earlier because of a leap year. Output requests are for separate graphs of TOPS and TNC on a time scale of 5 days. Printed output for YEAR, HAYHAR, HAYTOT, AW, DWS are also requested on a time scale of 10 days. Weather data are monthly averages (Division of Atmospheric Sciences, 1979 and 1980).

Source program listing in CSMP III:

```
*      ALSIM 1 (LEVEL 2): ALFALFA SIMULATOR WITH DAILY TIMESTEPS
*      USER'S MANUAL EXAMPLE
* ***
*      INITIAL SECTION
* ***
*      THE USER MUST SPECIFY THE VALUES APPROPRIATE FOR EACH RUN ON
*      CONSTANT, INCON, TABLE, AND FUNCTION CARDS OF THIS SECTION.
*      THEY ARE:
*
*      LAT, LATITUDE OF THE EXPERIMENTATION SITE IN DEGREES.
*      GDDB5I, GROWING DEGREE DAYS WITH 5C BASE FOR THE GROWTH PRESENT
*      AT THE START OF SIMULATION.
*      AWI, AVAILABLE WATER IN THE ROOT ZONE AT THE START OF
*      SIMULATION (MM).
*      AWFC, AVAILABLE WATER AT FIELD CAPACITY IN ROOT ZONE (MM).
*      LEAFI, YIELD OF LEAVES AT START OF SIMULATION (G/SQUARE METER).
*      STEMI, YIELD OF STEMS AT START OF SIMULATION (G/SQUARE METER).
*      TNCI, YIELD OF TNC AT START OF SIMULATION (G/SQUARE METER).
*      BUDI, YIELD OF BUDS AT START OF SIMULATION (G/SQUARE METER).
*      MATSI, YIELD OF MATS AT START OF SIMULATION (G/SQUARE METER).
*      YEAR, THE YEAR WHEN SIMULATION WAS STARTED.
*
*      THE CUTTING MANAGEMENT SECTION GENERATES A SIGNAL (CALLED CUT)
*      THAT WILL RESULT IN A SIMULATED HARVEST.  THE HARVEST IS
*      SIMULATED WHEN CUT EQUALS ONE.  THE USER INPUTS THE JULIAN DAYS
*      OF HARVESTS IN A TABLE, THUS:
*        TABLE  CDAY(1-3) = 160.,202.,245.
*      THIS WOULD RESULT IN THREE SIMULATED HARVESTS ON DAYS
*      160, 202, AND 245.  THE NUMBER OF HARVESTS MUST ALSO BE
*      SPECIFIED ON THE STORAGE CARD.  FOR TWO SIMULATED HARVESTS,
*      THAT CARD SHOULD READ:
*        STORAGE CDAY(2)
*      IF HARVESTS ARE NOT DESIRED, USE THE FOLLOWING STATEMENTS:
*        STORAGE CDAY(1)
*        TABLE CDAY(1) = 0.
*
*      WEATHER DATA FOR SOLAR RADIATION (LY/DAY), MINIMUM AND MAXIMUM
*      DAILY AIR TEMPERATURE (DEGREES C.), AND PRECIPITATION  (MM/DAY)
*      MUST BE PROVIDED IN A FORM COMPATIBLE WITH THE WEATHER SECTION.
*
**********     **********INITIAL SECTION DATA**********     **********
CONSTANT  LAT = 42.7,  YEAR=1979.
INCON GDDB5I = 0., AWI = 145., AWFC = 145.
INCON LEAFI = 0., STEMI = 0., TNCI = 100., BUDI = 10., MATSI = 0.
STORAGE  CDAY(4)
TABLE  CDAY(1-3) = 157.,200.,250.
* 1979
FUNCTION MAXTF= -15.5,36., 15.5,28., 32.,20., 59.,20., 74.5,46., ...
105.,52., 135.5,66., 166.,74., 182.,80., 212.,80., 227.5,76., ...
258.,71., 288.5,57., 319.,51., 349.5,39., 380.5,31.
FUNCTION MINTF= -15.5,21., 15.5,14., 32.,3., 59.,3., 74.5,28., ...
105.,34., 135.5,46., 166.,51., 182.,57., 212.,57., 227.5,56., ...
258.,48., 288.5,42., 319.,35., 349.5,25., 380.5,17.
FUNCTION SRADF= -15.5,82., 15.5,81., 45.,172., 74.5,244., 105.,290., ...
135.5,383., 166.,437., 182.,459., 212.,459., 227.5,361., 258.,336., ...
288.5,136., 319.,102., 335.,68., 365.,68., 380.5,96.
FUNCTION PPTF= 1.,3.7, 31.,3.7, 32.,1.5, 59.,1.5, 60.,1.8, 90.,1.8, ...
91.,2.8, 120.,2.8, 121.,1.8, 151.,1.8, 152.,2.3, 181.,2.3, 182.,1.8, ...

212.,1.8, 213.,3.9, 243.,3.9, 244.,3.6, 273.,3.6, 274.,3.4, 304.,3.4,...
305.,2.3, 334.,2.3, 335.,1.3, 365.,1.3
```

```
* ********     **INITIAL SECTION STRUCTURE STATEMENTS**     **********
INITIAL
       TNCM=TNCI
       NCUT = 1
       LATR = 2.*3.1416*LAT/360.
       COSUNR = (-SIN(LATR)*SIN(DECY))/(COS(LATR)*COS(DECY))
       DECY = 6.28/360.*23.45*SIN((TIME-81.)*6.28/360.*360./365.)
       SUNRIZ = ARCOS(COSUNR)*12./3.1416
       YDAYL = 2.*SUNRIZ
       SUMS1 = AMIN1(AWFC-AWI,U)
       SUMS2 = AMAX1(0.,AWFC-AWI-U)
       T = (SUMS2/ALPHA)**2
DYNAMIC
* ***
*      CUTTING MANAGEMENT SECTION
* ***
FIXED  NCUT
INCON  HLEAFI=0., HSTEMI=0.
PROCEDURE  CUT = CUTPRO(NCUT,CDAY)
       CUT = 0.
       IF (CDAY(NCUT).EQ.TIME) CUT = 1.
       NCUT = NCUT + CUT
ENDPRO
       TOPS = LEAF + STEM
       HLEAF = INTGRL(HLEAFI,HRL)
       HSTEM = INTGRL(HSTEMI,HRS)
       HAYHAR=INTGRL(0.,HRL+HRS-HAYHAR*CUT/DELT)
       HAYTOT = HLEAF + HSTEM
       FLHAY = HLEAF/(HAYTOT+NOT(HAYTOT))
* ***
*      CROP WEATHER SECTION
* ***
       MAXT = (5./9.)*(AFGEN(MAXTF,TIME)-32.)
       MINT = (5./9.)*(AFGEN(MINTF,TIME)-32.)
       SRAD = AFGEN(SRADF,TIME)
       PPT = AFGEN(PPTF,TIME)*IMPULS(1.,7.)*7.
       GDDB5 = INTGRL(GDDB5I,(DD-DDR-DDF)/DELT)
       DDF = INSW(KFROST-AVTA,0.,GDDB5)
       DD = AMAX1(0.,AVTA - 5.)
       DDR = GDDB5*CUT
       COSUNR = (-SIN(LATR)*SIN(DECR))/(COS(LATR)*COS(DECR))
       DECR = 6.2832/360.*23.45*SIN((TIME-80.)*6.2832/360.*360./365.)
       SUNRIZ = ARCOS(COSUNR)*12./3.1416
       DAYLIN = 2.*SUNRIZ
PROCEDURE  DAYLEN = DLPRO(DAYLIN,YDAYL)
       IF(DAYLIN-YDAYL) 10,20,20
   10  YDAYL = DAYLIN
       DAYLEN = (-1.)*DAYLIN
       GO TO 30
   20  DAYLEN = DAYLIN
       YDAYL = DAYLEN
   30  CONTINUE
ENDPRO
       FPS = AMIN1(SRAD/SRADM,1.)
       SRADM = 0.75*SUN
       SUN = 1440./3.14*1.95*(HA*SIN(LATR)*SIN(DECR)+...
            COS(LATR)*COS(DECR)*SIN(HA))

       HA = ARCOS(-TAN(DECR)*TAN(LATR))
       AVTA = (MAXT+MINT)/2.
       NRAD = ((1.-ALBEDO)*SRAD+TRAD)
       TRAD = (EMIS-0.97)*(118.E-9)*(273.+AVTA)**4*(1.35*FPS-0.35)
       EMIS = 1.-0.261*EXP(-7.77E-4*AVTA**2)
       ALBEDO = ALSOIL+0.25*(ALCROP-ALSOIL)*AMIN1(LAI,4.)
**********    ********* WEATHER SECTION DATA *********     **********
PARAMETER KFROST = 2.
PARAMETER ALCROP = .23,    ALSOIL = .2
```

```
* ***
*       EVAPOTRANSPIRATION SECTION
* ***
        AW = INTGRL(AWI,PPT+IRRIG-DRAIN-ET)
        IRRIG = 0.
        DRAIN = AMAX1(0.,AW+PPT+IRRIG-ET-AWFC)
        ET = EP+ES
        ES = AMIN1(EO-EP,ESR)
        EO = PTF*DG*NRAD/L
        ESO = PTFS*DG*NRADS/L
        PTFS = 0.92+0.4*(NRADS/NRAD)
        DG = 0.399+0.0167*AVTA-1.41E-4*AVTA**2
        NRADS = NRAD*EXP(-0.4*LAI)
        EP = AMIN1(EO,EO*(-.21+.7*AMAX1(.3,SQRT(LAI))),...
             (EO/AWFS)*AMAX1(0.,AW/AWFC))
        DWS = INTGRL(0.,NOT(AW/AWFC-AWFS))
        WSF = AMIN1(1.,AW/(AWFC*AWFS))
PROCEDURE ESR = ESRPRO(SUMS1,SUMS2,ESO,PPT,IRRIG,T,ALPHA,U,AWFC,AW)
      IF (SUMS1-U) 21, 27, 27
   21 IF (PPT+IRRIG-SUMS1) 22, 23, 23
   22 SUMS1 = AMAX1(SUMS1-PPT-IRRIG,AMIN1(U,AWFC+PPT+IRRIG-AW))
      GO TO 24
   23 SUMS1 = 0.
   24 SUMS1 = SUMS1+ESO
      IF (SUMS1-U) 25, 25, 26
   25 ESR =ESO
      T = 0.
      SUMS2 = 0.
      GO TO 39
   26 ESR = ESO-.4*(SUMS1-U)
      SUMS2 = .6*(SUMS1-U)
      T = (SUMS2/ALPHA)**2
      GO TO 39
   27 IF (PPT+IRRIG-SUMS2) 29, 28, 28
   28 P = PPT+IRRIG-SUMS2
      SUMS1 = U-P
      IF (P-U) 24, 24, 23
   29 T = T+1
      ESR = ALPHA*SQRT(T)-ALPHA*SQRT(T-1.)
      IF (PPT+IRRIG) 31,31, 33
   31 IF (ESR-ESO) 38, 38, 32
   32 ESR = ESO
      GO TO 38
   33 ESX = .8*(PPT+IRRIG)
      IF (ESX-ESR) 34, 34, 35
   34 ESX = ESR+PPT+IRRIG
   35 IF (ESX-ESO) 37, 37, 36
   36 ESX = ESO
   37 ESR = ESX
   38 SUMS2 = AMAX1(SUMS2+ESR-PPT-IRRIG,AWFC+PPT+IRRIG-AW-U)

      T = (SUMS2/ALPHA)**2
      SUMS1 = U
   39 CONTINUE
ENDPRO
**********     *    EVAPOTRANSPIRATION SECTION DATA     *      **********
PARAMETER  U=10., ALPHA=4.5, AWFS=.50
CONSTANT   L=58., PTF=1.32
```

```
* ***
*      MATS SECTION:  MATERIALS AVAILABLE FOR TOP GROWTH AND STORAGE
* ***
       GRM=AFGEN(GFASR,SRADA)*AFGEN(ETG,AVTA)*AFGEN(ESPM,GDDB5) ...
           *(1.-CUT)*WSF
       MATS = INTGRL(MATSI,GRM-GRL-GRS-STOR-OUM)
       OUM = DTGR-GRL-GRS-STOR
       SRADA = SRAD*FSRADA
       FSRADA = LDAB+(SDAB-LDAB)*DLFAC
       DLFAC = LIMIT(0.,15.-12.,15.-DAYLIN)/(15.-12.)
       SDAB = AFGEN(SDABT,LAI)
       LDAB = AFGEN(LDABT,LAI)
       DTGR = MATS/DELT
**********     **********  MATS SECTION DATA **********     **********
FUNCTION GFASR = 0.,0.,.0001,0.,  100.,5.8,  200.,10.4,  300.,14.2,  ...
       400.,16.9,  500.,19.0,  600.,21.1,  700.,23.1,  800.,25.0
FUNCTION   ETG = -30.,0.,  2.,0.,  5.,.2,  10.,.95,  12.,1.,  15.,1.,...
         21.,.92,  27.,.66,  32.,.36,  40.,.05,  50.,0.
FUNCTION  ESPM = 0.,.95,  125.,1.,  700.,1.,  750.,.95,  875.,.7,    ...
         1000.,.6,  2000.,.35,  4000.,.25
FUNCTION  SDABT = 0.,0.,  .5,.55,  .75,.70,  1.,.80,          ...
                  1.5,.90,  2.,.95,  15.,.999
FUNCTION  LDABT = 0.,0.,   .5,.30,  .75,.42,  1.,.50,         ...
                  1.5,.65,  2.,.75,  3.,.90,  4.,.95,  15.,.999
* ***
*      LEAF SECTION
* ***
       LEAF  = INTGRL(LEAFI,GRL+GRLB-LOSSL)
       GRL = AMIN1(DTGR*FTGL,PGRL)*(1.-CUT)*WSF
       FTGL = AFGEN(FTGLF,LEAF)
       PGRL = 0.2*LEAF*AFGEN(ELLG,LEAF)*AFGEN(EDLG,DAYLEN)
       SRL = AMAX1(0.,(LEAF-CLEAF)/DTL)
       CLEAF = (LDCLAI-DLFAC*(LDCLAI-SDCLAI))/SLA
       LOSSL = AMAX1(HRL,SRL,FRL)
       FRL = INSW(KFROST-AVTA,0.,LEAF/DELT)
       LAI = AMAX1(0.,SLA*LEAF)
       FLEAF = LEAF/(LEAF+STEM+NOT(LEAF+STEM))
       HRL = LEAF*CUT/DELT
**********     **********  LEAF SECTION DATA **********     **********
PARAMETER  SLA = .02
PARAMETER  DTL = 7.,   SDCLAI = 1.5,  LDCLAI = 5.
FUNCTION  FTGLF = 0.,.9,  190.,.42,  250.,.4,  350.,.4
FUNCTION   ELLG = 0.,1.,  100.,1.,  110.,.95,  120.,.8,  145.,.40, ...
            155.,.20,  165.,.10,  200.,.05,  350.,0.
FUNCTION  EDLG = -16.,1.,  -14.,.7,    -10.5,.15,             ...
         -10.,.1,  4.,.1,  4.5,.15,  8.5,.95,  9.,1.,  16.,1.
* ***
*      STEM SECTION
* ***
       STEM  = INTGRL(STEMI,GRS+GRSB-LOSSS)
       GRS = AMIN1(DTGR*(1.-FTGL),PGRS)*(1.-CUT)*WSF
       PGRS = 0.499*STEM*AFGEN(ESSG,STEM)*AFGEN(EDSG,DAYLEN)

       SRS = AMAX1(0.,(STEM-CSTEM)/DTS)
       CSTEM = TOPS*CSF
       LOSSS = AMAX1(HRS,SRS,FRS)
       FRS = INSW(KFROST-AVTA,0.,STEM/DELT)
       HRS = STEM*CUT/DELT
**********     **********  STEM SECTION DATA **********     **********
PARAMETER  CSF = .75,  DTS = 14.
FUNCTION   ESSG = 0.,1.,  155.,1.,  175.,.95,  205.,.8,  240.,.3, ...
            265.,.1,  285.,.05,  500.,0.
FUNCTION  EDSG = -16.,1.,  -14.,.7,   -12.5,.25,              ...
         -12.,.15,  -11.5,.1,  -10.5,.05,  9.,.05,  9.5,.1,         ...
         10.5,.4,  12.5,.9,  13.,1.,  16.,1.
```

```
* ***
*       TNC SECTION
* ***
        TNC = INTGRL(TNCI,STOR-GRB-TRESP)
        STOR = AMIN1(DTGR-GRL-GRS,PSTOR)*(1.-CUT)
        PSTOR = 3.5*AFGEN(EDS,DAYLEN)*AFGEN(ETNCS,TNC)+GRB+TRESP
PROCEDURE TNCS=TNCPRO(TNC,TNCM)
        TNCS=AMAX1(TNC,TNCM)
        TNCM=TNCS
ENDPRO
        MLOSS = TNCS*MLOSC*NOT(GRM)
        TRESP = MLOSS+GRB*RCTNC/(1.-RCTNC)
**********     **********  TNC SECTION DATA  **********     **********
CONST MLOSC = 0.00093
FUNCTION  ETNCS = 0.,1.,  80.,1.,  90.,.9,  100.,.5,  110.,.1,        ...
          140.,.05,  150.,0.
FUNCTION  EDS = -16.,.5, -15.,.9, -14.,1., -6.,1.,  ...
         6.,.286, 14.,.286, 15.,.35, 16.,.5
* ***
*       BUD SECTION
* ***
        BUDS = INTGRL(BUDI,GRB-GRLB-GRSB)
        GRSB = GRLB*.1
        BUDC = AFGEN(BUDCF,TNC)
        BEF = INSW(MATS*(-1),AFGEN(BEFSR,SRADN),1.)* ...
              AFGEN(BEFD,DAYLEN)*AFGEN(BEFT,AVTA)
        GRLB = (BUDS/MLBUDS)*BEF*WSF
        GRB = (1.-RCTNC)*AMIN1((BUDC-BUDS)/(1.-RCTNC),TNC/MLTNC, ...
              RGR*(TOPS+BUDS))*AFGEN(ETG,AVTA)
        SRADN = SRAD-SRADA
**********     **********  BUD SECTION DATA  **********     **********
PARAMETER  RCTNC = .6, RGR = .5, MLBUDS = 2., MLTNC = 14.
FUNCTION  BUDCF = 0.,5.,  50.,8.,  100.,12.,  125.,15.,  150.,20.
FUNCTION  BEFSR = 0.,0.,  30.,0.,  40.,.05,  50.,.15, 80.,.85,        ...
          90.,.95,  100.,1.,  800.,1.
FUNCTION  BEFD = -16.,1., -14.,1., -12.,.9, -11.,0., ...
          11.,0., 12.,.9, 14.,1., 16.,1.
FUNCTION BEFT = -20.,0., 5.,0., 8.,1., 50.,1.
* ***
*       CROP DEATH SECTION
* ***
CONSTANT   DEATH = 0.
        CCOND = IOR(TNCD,GRM)
        TNCD = TNC-5.
* ***
*       COMPUTE INITIAL CONDITIONS FOR NEXT SIMULATED YEAR
* ***

TERMINAL
        YEAR=YEAR+NOT(365.-TIME)
        HLEAFI=HLEAF
        HSTEMI=HSTEM
        GDDB5I=GDDB5
        AWI=AW
        LEAFI=LEAF
        STEMI=STEM
        TNCI=TNC
        BUDI=BUDS
        MATSI=MATS
METHOD  RECT
FINISH  DEATH = CCOND
```

```
* ***
*      RUN CONTROL SECTION
* ***
TIMER DELT = 1., FINTIM = 365., PRDEL = 10., TIME =65.,  OUTDEL=5.
TITLE  USER'S MANUAL EXAMPLE--1979 WEATHER
PRINT  YEAR,HAYHAR,HAYTOT,AW,DWS
OUTPUT TOPS
OUTPUT TNC
END
TITLE  1980 WEATHER
* 1980 - LEAP YEAR
FUNCTION MAXTF= -15.5,39., 15.5,31., 45.,27., 75.5,37., 106.,55., ...
136.5,68., 167.,73., 183.,80., 244.,80., 259.,73., 289.5,54., ...
320.,42., 350.5,32., 367.,25., 397.,25.
FUNCTION MINTF= -15.5,25., 15.5,17., 45.,13., 75.5,22., 106.,35., ...
136.5,44., 167.,49., 197.5,57., 214.,60., 244.,60., 259.,50., ...
289.5,37., 320.,29., 350.5,12., 367.,6., 397.,6.
FUNCTION SRADF= -15.5,68., 15.5,96., 45.,162., 75.5,221., 106.,299., ...
136.5,432., 153.,437., 182.,437., 197.5,437., 228.5,397., 259.,357., ...
289.5,180., 320.,102., 350.5,101., 381.5,143.
FUNCTION PPTF= 1.,.4, 31.,.4, 32.,.5, 60.,.5, 61.,4.2, 91.,4.2, ...
92.,2.7, 121.,2.7, 122.,1.1, 152.,1.1, 153.,3.5, 182.,3.5, 183.,2.8, ...
213.,2.8, 214.,2.7, 244.,2.7, 245.,1.9, 274.,1.9, 275.,2.9, 305.,2.9,...
306.,1.9, 335.,1.9, 336.,1.6, 366.,1.6
TIMER  TIME = 1., FINTIM =281.
END
```

The output generated by this program follows. The output requested on the PRINT statement is presented first. Yields (HAYHAR, HAYTOT, TOPS, TNC) are in units of g m^{-2}. Water supply (AW) is in mm. Time (TIME, DWS) is in units of days, excepting the variable YEAR).

USER'S MANUAL EXAMPLE--1979 WEATHER

TIME	YEAR	HAYHAR	HAYTOT	AW	DWS
65.0000	1979.0	.0	.0	145.00	.0
75.0000	1979.0	.0	.0	141.05	.0
85.0000	1979.0	.0	.0	135.96	.0
95.0000	1979.0	.0	.0	141.33	.0
105.000	1979.0	.0	.0	135.81	.0
115.000	1979.0	.0	.0	142.57	.0
125.000	1979.0	.0	.0	134.02	.0
135.000	1979.0	.0	.0	129.16	.0
145.000	1979.0	.0	.0	108.33	.0
155.000	1979.0	.0	.0	84.985	.0
165.000	1979.0	532.68	532.68	88.854	.0
175.000	1979.0	532.68	532.68	89.280	.0
185.000	1979.0	532.68	532.68	74.541	1.0000
195.000	1979.0	532.68	532.68	47.857	10.000
205.000	1979.0	384.31	917.00	49.951	20.000
215.000	1979.0	384.31	917.00	47.009	30.000
225.000	1979.0	384.31	917.00	48.068	40.000
235.000	1979.0	384.31	917.00	71.825	48.000
245.000	1979.0	384.31	917.00	69.042	54.000
255.000	1979.0	320.76	1237.8	98.890	56.000
265.000	1979.0	320.76	1237.8	113.05	56.000
275.000	1979.0	320.76	1237.8	145.00	56.000
285.000	1979.0	320.76	1237.8	141.31	56.000
295.000	1979.0	320.76	1237.8	139.16	56.000
305.000	1979.0	320.76	1237.8	143.46	56.000
315.000	1979.0	320.76	1237.8	141.79	56.000
325.000	1979.0	320.76	1237.8	144.50	56.000
335.000	1979.0	320.76	1237.8	143.22	56.000
345.000	1979.0	320.76	1237.8	145.00	56.000
355.000	1979.0	320.76	1237.8	143.94	56.000
365.000	1979.0	320.76	1237.8	142.95	56.000

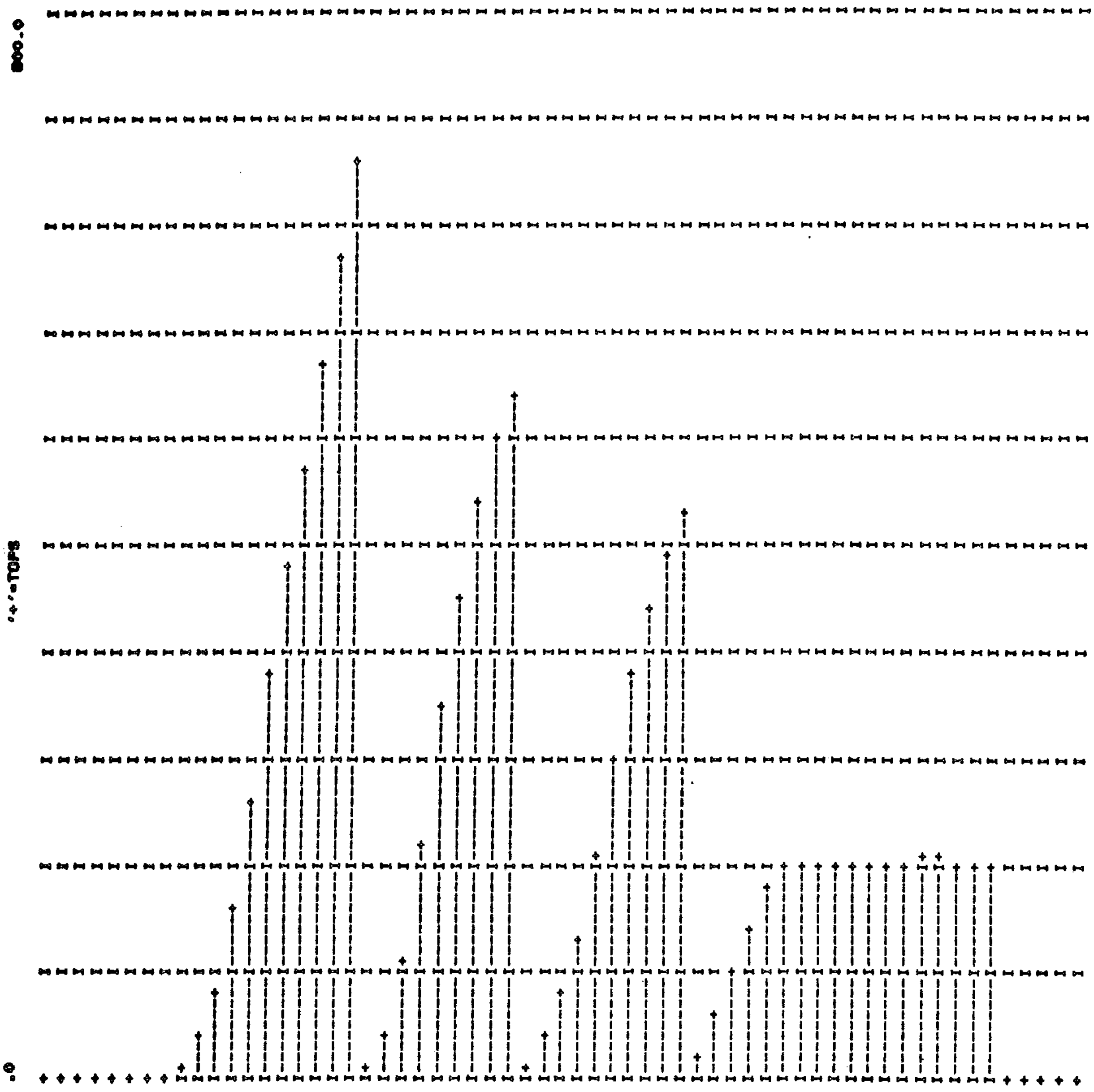
$$$ SIMULATION HALTED FOR FINISH CONDITION TIME 365.00

1980 WEATHER

TIME	YEAR	HAYHAR	HAYTOT	AW	DWS
1.00000	1980.0	.0	1237.8	142.95	.0
11.0000	1980.0	.0	1237.8	144.33	.0
21.0000	1980.0	.0	1237.8	143.18	.0
31.0000	1980.0	.0	1237.8	144.49	.0
41.0000	1980.0	.0	1237.8	142.98	.0
51.0000	1980.0	.0	1237.8	144.22	.0
61.0000	1980.0	.0	1237.8	140.79	.0
71.0000	1980.0	.0	1237.8	139.15	.0
81.0000	1980.0	.0	1237.8	142.45	.0
91.0000	1980.0	.0	1237.8	137.24	.0
101.000	1980.0	.0	1237.8	143.02	.0
111.000	1980.0	.0	1237.8	135.72	.0
121.000	1980.0	.0	1237.8	145.00	.0
131.000	1980.0	.0	1237.8	122.26	.0
141.000	1980.0	.0	1237.8	95.095	.0
151.000	1980.0	.0	1237.8	73.578	.0
161.000	1980.0	559.11	1796.9	71.765	7.0000
171.000	1980.0	559.11	1796.9	100.69	9.0000
181.000	1980.0	559.11	1796.9	88.261	9.0000
191.000	1980.0	559.11	1796.9	85.073	10.000
201.000	1980.0	442.79	2239.7	62.998	16.000
211.000	1980.0	442.79	2239.7	70.219	21.000
221.000	1980.0	442.79	2239.7	76.477	24.000
231.000	1980.0	442.79	2239.7	57.993	31.000
241.000	1980.0	442.79	2239.7	63.224	41.000
251.000	1980.0	350.72	2590.4	48.915	51.000
261.000	1980.0	350.72	2590.4	65.401	61.000
271.000	1980.0	350.72	2590.4	64.855	71.000
281.000	1980.0	350.72	2590.4	64.287	81.000

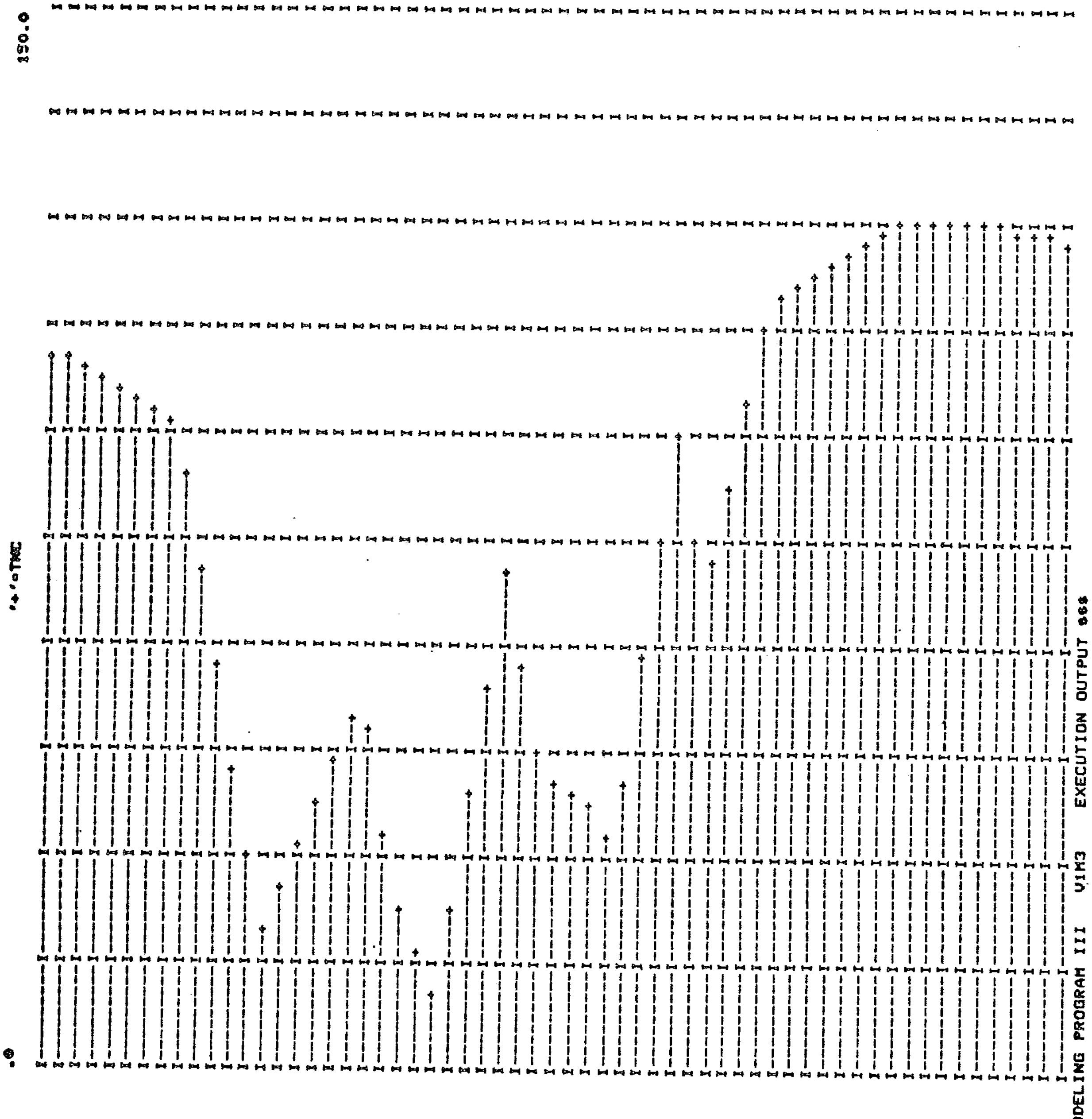
$$$ SIMULATION HALTED FOR FINISH CONDITION TIME 281.00

1979 top growth:



TIME	TOPS
65.000	.0
70.000	.0
75.000	.0
80.000	.0
85.000	.0
90.000	.0
95.000	.0
100.00	2.2765
105.00	8.5798
110.00	24.527
115.00	52.367
120.00	98.815
125.00	158.06
130.00	227.94
135.00	285.38
140.00	343.30
145.00	401.20
150.00	459.11
155.00	514.91
160.00	8.4982
165.00	26.120
170.00	69.160
175.00	134.27
180.00	210.48
185.00	272.34
190.00	321.55
195.00	358.26
200.00	384.31
205.00	9.8372
210.00	27.142
215.00	52.553
220.00	81.589
225.00	127.63
230.00	180.63
235.00	229.75
240.00	263.26
245.00	293.59
250.00	320.76
255.00	15.252
260.00	36.036
265.00	62.043
270.00	88.165
275.00	108.65
280.00	119.50
285.00	123.60
290.00	124.06
295.00	122.67
300.00	121.38
305.00	120.70
310.00	121.45
315.00	124.05
320.00	126.43
325.00	126.35
330.00	124.59
335.00	122.90
340.00	121.29
345.00	.0
350.00	.0
355.00	.0
360.00	.0
365.00	.0

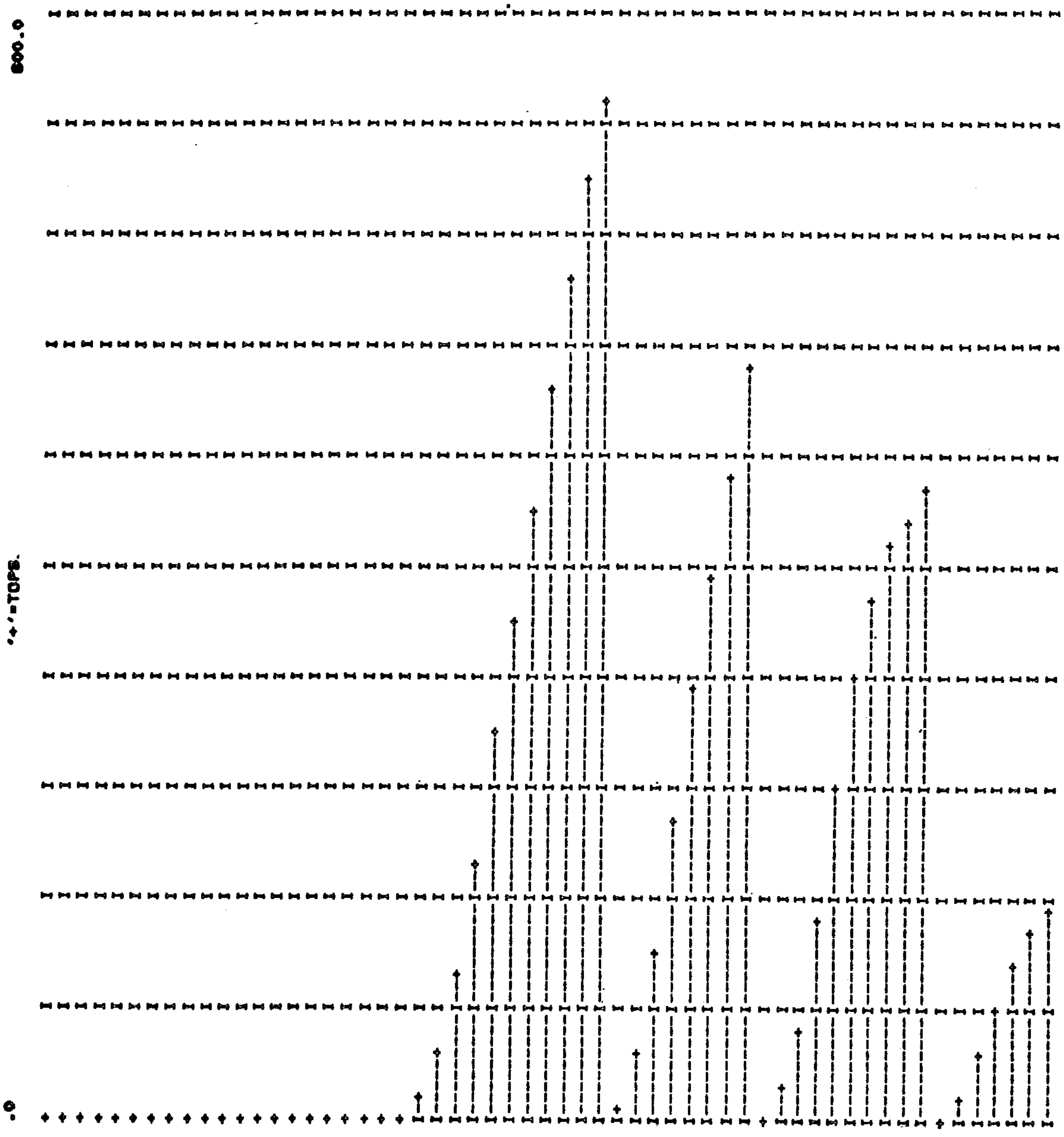
1979 TNC pattern:



TIME	TNC
65.000	100.00
70.000	99.535
75.000	98.867
80.000	97.125
85.000	95.462
90.000	94.302
95.000	93.579
100.00	92.103
105.00	83.377
110.00	71.131
115.00	56.813
120.00	42.445
125.00	29.958
130.00	20.816
135.00	26.233
140.00	31.844
145.00	37.629
150.00	43.565
155.00	49.629
160.00	48.081
165.00	33.445
170.00	23.347
175.00	16.384
180.00	11.558
185.00	23.047
190.00	38.696
195.00	54.598
200.00	70.710
205.00	57.681
210.00	45.040
215.00	40.338
220.00	39.008
225.00	38.148
230.00	32.785
235.00	40.484
240.00	57.984
245.00	74.657
250.00	89.908
255.00	75.318
260.00	72.555
265.00	81.725
270.00	94.959
275.00	104.25
280.00	108.62
285.00	110.73
290.00	112.44
295.00	114.10
300.00	115.71
305.00	117.27
310.00	118.79
315.00	119.93
320.00	119.86
325.00	119.86
330.00	119.86
335.00	119.86
340.00	119.86
345.00	119.30
350.00	118.74
355.00	118.19
360.00	117.63
365.00	117.07

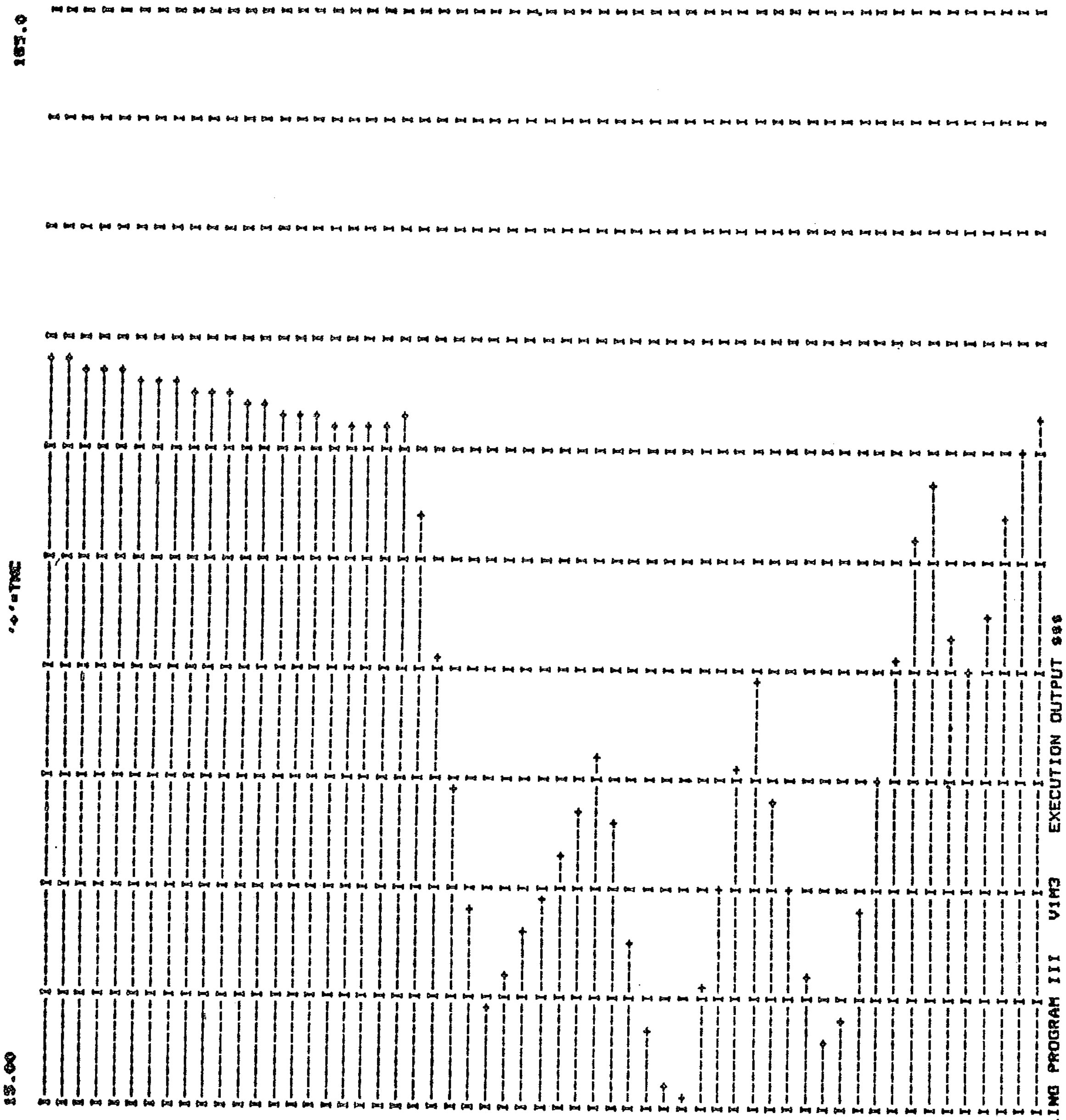
$$ CONTINUOUS SYSTEM MODELING PROGRAM III V1M3 EXECUTION OUTPUT $$

1980 top growth:



TIME	TOPS
1.0000	.0
6.0000	.0
11.000	.0
16.000	.0
21.000	.0
26.000	.0
31.000	.0
36.000	.0
41.000	.0
46.000	.0
51.000	.0
56.000	.0
61.000	.0
66.000	.0
71.000	.0
76.000	.0
81.000	.0
86.000	.0
91.000	.0
96.000	.0
101.00	1.7442
106.00	14.636
111.00	39.359
116.00	80.647
121.00	139.42
126.00	209.92
131.00	272.15
136.00	331.97
141.00	392.94
146.00	453.03
151.00	510.63
156.00	550.62
161.00	10.521
166.00	37.636
171.00	90.837
176.00	162.73
181.00	237.39
186.00	294.01
191.00	350.09
196.00	405.20
201.00	.0
206.00	19.246
211.00	51.161
216.00	110.20
221.00	180.16
226.00	240.23
231.00	283.84
236.00	311.44
241.00	326.71
246.00	341.58
251.00	.0
256.00	17.616
261.00	37.522
266.00	62.226
271.00	85.123
276.00	103.18
281.00	113.54

1980 TNC pattern:



TIME	TNC
1.0000	117.07
6.0000	116.53
11.000	115.98
16.000	115.44
21.000	114.89
26.000	114.35
31.000	113.80
36.000	113.25
41.000	112.71
46.000	112.17
51.000	111.63
56.000	111.08
61.000	110.54
66.000	109.99
71.000	109.45
76.000	108.90
81.000	108.36
86.000	107.81
91.000	107.58
96.000	106.36
101.00	106.88
106.00	55.561
111.00	76.951
116.00	58.570
121.00	42.120
126.00	28.463
131.00	33.584
136.00	39.042
141.00	44.689
146.00	50.506
151.00	56.469
156.00	62.555
161.00	54.719
166.00	37.973
171.00	26.394
176.00	18.435
181.00	16.528
186.00	31.520
191.00	46.044
196.00	61.985
201.00	74.136
206.00	57.122
211.00	45.651
216.00	33.441
221.00	24.475
226.00	27.758
231.00	42.999
236.00	60.005
241.00	76.753
246.00	93.453
251.00	101.04
256.00	80.337
261.00	75.272
266.00	82.078
271.00	95.654
276.00	104.58
281.00	108.77

$$$ CONTINUOUS SYSTEM MODELING PROGRAM III V1M3 EXECUTION OUTPUT $$$

ACKNOWLEDGMENTS

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