Simulated effects of supplementary water on two grasslands, Agropyron Smithii and Bouteloua gracilis
by Carol Ann Johnson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biological Sciences
Montana State University

Abstract:
Supplemental water, either supplied by irrigation or cloud-seeding, is a possible means of increasing forage yield of rangeland (Perry 1976). A computer model (Wight and Hanks 1981) was tested for its ability to accurately predict forage yield, by comparing simulated soil water and plant yield data with field-measured values from twenty-two dryland and irrigated plots at two grassland sites in eastern Montana (Weaver et al., 1981). The model was modified slightly to better "fit" the field data, and the modified model was used to simulate ten water supplementation strategies in a variety of years. The nine simulated years varied from the driest years to the wettest years in an eighty year record for Miles City, Montana (USDC 1903-1983). Three general supplementation strategies were employed, to test the effectiveness of both amount and timing of additional water. Water supplements (2.5 cm, 5.1 cm, and 10.2 cm) were applied before the growing season began, natural precipitation events were augmented during the growing season, and single showers (2.5 cm) were applied at various times (1 April, 15 May, 15 June, or 15 July) during the growing season. Two limited augmentation strategies were compared to augmentation of all natural rain events, as well. This series of treatments, compared in a variety of years, supported two generalizations about the simulated water supplementation strategies. First, pre-season water application increased plant yield, and was most effective in years when the soil was dry before the season began. Increased availability of supplemental water to plant use, due both to low evaporative demand and to storage of water in deep soil layers, contributed to the effectiveness and efficiency of pre-season supplements. Second, application of water during the growing season was inefficient, due to evaporative water losses, and seldom effected large increases in plant yield. Therefore, water supplementation for "drought relief", when the soil is already dry, is not likely to increase yield. In years when soil water storage is available, preseason or early-season supplementation might be effective in reducing or preventing the effects of drought.

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Carol Ann Johnson

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Supplemental water, either supplied by irrigation or cloud-seeding, is a possible means of increasing forage yield of rangeland (Perry 1976). A computer model (Wight and Hanks 1981) was tested for its ability to accurately predict forage yield, by comparing simulated soil water and plant yield data with field-measured values from twenty-two dryland and irrigated plots at two grassland sites in eastern Montana (Weaver et al., 1981). The model was modified slightly to better "fit" the field data, and the modified model was used to simulate ten water supplementation strategies in a variety of years. The nine simulated years varied from the driest years to the wettest years in an eighty year record for Miles City, Montana (USDC 1903-1983). Three general supplementation strategies were employed, to test the effectiveness of both amount and timing of additional water. Water supplements (2.5 cm, 5.1 cm, and 10.2 cm) were applied before the growing season began, natural precipitation events were augmented during the growing season, and single showers (2.5 cm) were applied at various times (1 April, 15 May, 15 June, or 15 July) during the growing season. Two limited augmentation strategies were compared to augmentation of all natural rain events, as well. This series of treatments, compared in a variety of years, supported two generalizations about the simulated water supplementation strategies. First, pre-season water application increased plant yield, and was most effective in years when the soil was dry before the season began. Increased availability of supplemental water to plant use, due both to low evaporative demand and to storage of water in deep soil layers, contributed to the effectiveness and efficiency of pre-season supplements. Second, application of water during the growing season was inefficient, due to evaporative water losses, and seldom effected large increases in plant yield. Therefore, water supplementation for "drought relief", when the soil is already dry, is not likely to increase yield. In years when soil water storage is available, pre-season or early-season supplementation might be effective in reducing or preventing the effects of drought.

INTRODUCTION

Water is a major limiting factor for plant growth throughout much of the world (World Meteorological Organization 1975, Coupland 1958). Cloud seeding techniques have therefore been studied for decades as a possible mechanism for increasing crop or forage production (Cooper and Jolly 1969). In the semi-arid lands of the Northern Great Plains, for example, resultant rainfall increases due to weather modification might be quite large (Weinstein 1972).

It is difficult to determine the practicality of a cloud-seeding program, in part, because it is difficult to estimate production increases for various rainfall regimes. This difficulty is largely due to the complex response of agricultural or grassland ecosystems to additional water. The response depends on climatic variables, including temperature, insolation, precipitation, and season of application, as well as on soil and plant characteristics. Many have investigated separate environmental, edaphic and physiological factors which determine plant response to additional water (Perry 1976). Combination of the separate factors and their interactions through modeling should allow a more complete view of the system.

Three approaches have been used to estimate ecosystem response to additional water. These include irrigation studies, regression methods and computer simulation. Irrigation studies have been used to measure native range response to additional water (Weaver 1981, Sala and Lauenroth 1982, Haglund 1981). Unfortunately, money, time, and space constraints limit the number of regimes that can be tested experimentally. Regression methods are site specific and are usually limited in the number of variables considered. For example, precipitation is often correlated with yield (Smoliak 1956; Shiflet and Dietz 1974); soil moisture may be regressed with respect to yield (review, Veihmeyer and Hendrickson 1950, Rogler and Haas 1947), or evapotranspiration may be related to yield (review, Stewart et al. 1976). In contrast, computer simulation is a flexible and economical approach, and one that can simultaneously treat a large number of variables and their relationships to each other. Computer models have been developed to estimate the climate and yield relationship for specific crops, including wheat (Hanks 1974), sorghum (Arkin et al. 1976), corn (Morgan et al. 1980), soybeans (Hill 1979), and others (Johnson and Weaver 1981). Only a few models evaluate native plant system responses to environmental variables, however. Among these are the Ritchie et al. (1976) model for predicting evapotranspiration from native rangeland, the de Jong and MacDonald (1975) simulation of soil moisture regimes in native grasslands, and the comprehensive grassland ecosystem model developed by the U.S. International Biological Program (Innis 1978).

The object of this study was to compare several cloud seeding strategies in terms of native plant growth. A computer model developed by Wight and Hanks (1981) was chosen as a basis for achieving this end because all required input data were available. It was run and tested with an existing data set, which included five years of climatic data, soil moisture data, and plant growth data from two grassland sites in eastern Montana (Weaver 1981). After several slight modifications to the model, the simulated soil water and yield values and the field data corresponded reasonably well. Historic climatic data wasthen used to run the modified model, in order to compare the effects of several different water supplementation strategies.

METHODS

The model (Wight and Hanks 1981) was first tested to determine whether its water addition and removal functions correctly predicted field-measured values of soil moisture. The predicted plant growth (yield) indices were also compared to measured values of plant production. With several changes, the model was made to accurately simulate ("fit") five years (1977-1981) data from an available field data set. The modified model's soil water and plant growth functions seemed to operate in a realistic manner. The model fit was further tested (validated) by comparing simulated data with field data from six irrigation treatments applied in 1977; this validated the model's ability to accurately predict plant growth in plots given supplementary water. Historic precipitation data was then supplemented by varying additions, to compare the effects of a series of water supplements, which could be related to different cloud-seeding strategies. The precipitation manipulations were compared in dry, average, and wet years to determine what conditions and supplementation strategies promised the greatest benefits.

Field Data

Field data from two sites near Miles City, Montana, were used to fit, modify, and validate the model. One of the sites is dominated by Agropyron smithii (Agropyron), the other by Bouteloua gracilis

(Bouteloua); both grassland types are representative of large areas of the Northern Great Plains (Kuchler, 1964). Weather data (driving variables), site characteristics (state variables), and soil water and production data (test variables) were available for irrigated and unirrigated plots over five years (1977-1981) (Weaver et al. 1981).

Five years (1977 to 1981) of precipitation and maximum-minimum air temperature data from both sites were available for use as driving variables in fitting and validation simulations. Annual precipitation (October to September) for these years ranged from 22.3 cm (1980) to 53.6 cm (1978). This represents the entire range in precipitation at Miles City over the last eighty years (16.8 cm in 1931 to 60.1 cm in 1972), (U.S. Dept. of Commerce 1903-1983).

Soil water data from both sites were available to fit and validate the model's soil water predictions. Weaver et al. (1981) used gypsum blocks (Taylor et al. 1961, and Taylor and Ashcroft 1972) to estimate soil moisture in control plots (used for model fitting) and in irrigated treatments (used for model validation). Weaver et al. (1981) made weekly measurements throughout each growing season of the five year study (1977-1981). Each week, six measurements were taken at each of three depths (10, 25, 75 cm) in each treatment. For the present study, the mean of the six values was determined for each depth and week, and compared to model-predicted soil water for each depth and week. The model calculates gravimetric water contents for each layer; therefore, block resistance readings were calibrated against gravimetric water content samples (1981) for three of the four soil layers modeled in this study, and for each site, over a wide range of water contents (Appendix A). The soil layers modeled, (and the corresponding block depths), were 0-10 cm (10 cm), 10-30 cm (25 cm), 30-50 cm (none), and 50-100 cm (75 cm).

Biomass data, collected monthly between May and October (1977-1981) at each site (Weaver et al. 1981), were used to fit and validate model production estimates. These data were used to estimate standing crop for each date, as well as the date of peak standing crop.

Soil water and production measures were made on both irrigated and dryland plots in the period 1977-1981. The unirrigated plot data were used to "fit" the model, or adjust the model to the sites. Five irrigation treatments were applied to previously unirrigated plots in 1977, and these data were used to validate, or verify, the model fit. The five irrigation treatments established by Weaver (1981) were a "spring wet" plot, (25 mm supplemental water per week until soil profile is filled to 75 cm), a plot guaranteed 6 mm of water per week (precipitation augmented by irrigation when rainfall was less than 6 mm), a plot guaranteed 12 mm of water per fortnight (c.f. above), a "wet" plot, (25 mm supplemental irrigation per week regardless of precipitation record), and a "fall wet" plot (soil profile filled to 75 cm in late September of the previous year).

A more complete description of sites, treatments, and observations is provided by Weaver (1981).

The Model

The Ekalaka Rangeland Hydrology and Yield Model, ERHYM, (Wight and Hanks 1981) was used in this study because it is relatively simple, requiring only four driving variables, as well as state variables, including soil, plant, and runoff parameters. The driving variables are daily precipitation, minimum and maximum air temperatures and solar radiation.

Water enters the system as precipitation, and may leave the system as either runoff, deep drainage, evaporation or plant transpiration (Figure 1). When rain falls, progressively deeper soil layers are filled to field capacity, and excess water drains to the next layer. Water may be lost from the system as runoff, or, if layers are filled, may move out of the system as deep drainage. Soil evaporation and plant transpiration, in that order, remove water from the soil profile, beginning with the uppermost layer. The potential evapotranspirative demand is calculated with the Jensen and Haise (1963) evapotranspiration equation. The potential demand is partitioned into potential transpiration and potential evaporation; these values are used to calculate actual transpiration and evaporation.

Water budget and plant growth calculations are summarized in the following paragraphs and in Figure 2.

Water enters the system as rainfall or as snowmelt. Daily precipitation records are input to the model (Step 1), and snowmelt is calculated on the basis of average temperature and a snowmelt factor (=0.18). Initial water content of the soil profile is an input parameter.

The runoff calculations in ERHYM (Step 11) use the Soil Conservation Service (SCS) curve number technique and are taken

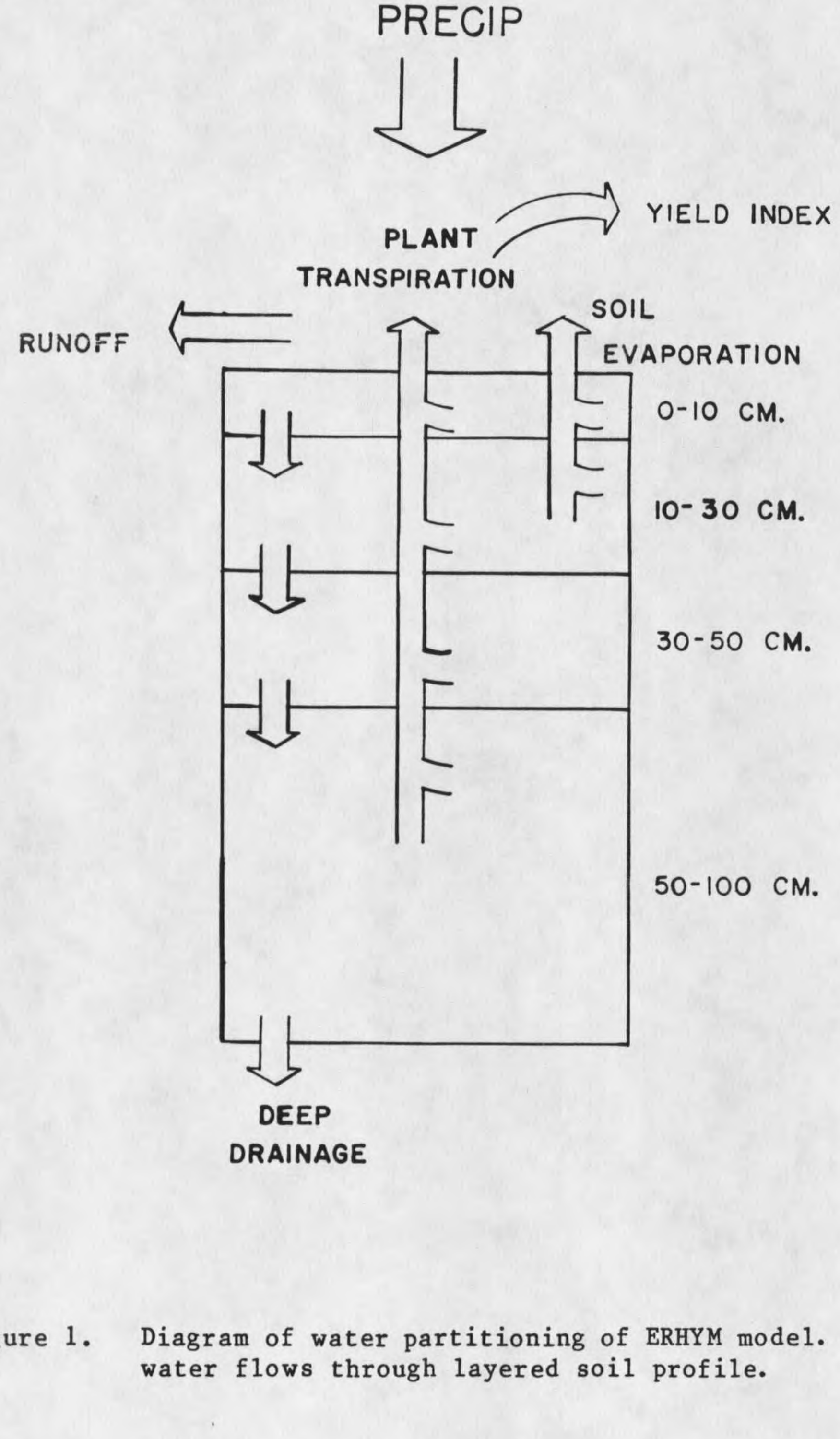

Figure 1. Diagram of water partitioning of ERHYM model. Shows major water flows through layered soil profile.

Step 1		Read day's precipitation, minimum & maximum air temperatures, and solar radiation (SOLARR).
Step 2	EO:	Calculate Jensen-Haise potential evapotranspiration (EO). EO = ((0.14 * average temperature) - 0.37) * SOLARR/580.0
Step 3	RGC:	Compute relative growth value (=LAI) from curve [RGC].
Step 4	PET:	Reduce EO by crop coefficient (CROPCO) to calculate potential evapotranspiration from rangeland (PET). PET = EO * CROPCO
Step 5		Partition PET into potential evaporation (PEVAP) and potential transpiration (PTRAN).
Step 6	PTRAN:	Reduce PET by transpiration coefficient (TRANCO) and [RGC] to calculate potential transpiration (PTRAN). PTRAN = PET * TRANCO * RGC
Step 7	PEVAP:	Reduce PET by PTRAN to calculate potential evaporation (PEVAP). PEVAP = PET - PTRAN
Step 8	AEVAP:	Actual evaporation (AEVAP) is equal to amount of rain if it is greater than 0 and less than PEVAP.
Step 9	AEVAP:	Reduce PEVAP by (number of days since rain)$^{-1/2}$ (t) AEVAP = PEVAP * $t^{-1/2}$
Step 10		Compute snowpack, snowmelt, and available water entering soil.
Step 11	RO:	Compute runoff, peak flow [=0.0]; reduce available water entering soil by these values.
Step 12		Add water to soil layers, filling each layer to field capacity; excess water moves to next layer.
Step 13	DD:	Calculate deep drainage (DD), amount of water moving out of soil profile.
Step 14	AEVAP:	Evaporate water from snowpack and then from top 30 cm of soil to air-dry value (AIRDRY) only.
Step 15	ATRAN:	Reduce PTRAN by [soil water percentage factor] and root factor [ROOTF=1.0]; remove actual transpiration (ATRAN) from soil layers, drawing from progressively deeper layers, till PTRAN demand is met, or lower bound of plant available water (UNASM) is reached.
Step 16	CTATRN:	Accumulate actual transpiration [occurring at soil water potentials greater than -1.5 MPa].
Step 17	CTPTRN:	Accumulate potential transpiration (PTRAN)
Step 18		Yield index = CTATRN / CTPTRN (cumulative)

Figure 2. Water budget and plant growth calculations in ERHYM. Brackets indicate modifications which were made to original model functions or calculations.

directly from Smith and Williams (1980). Parameters required are field size, channel slope, a watershed length-width ratio, the Condition II SCS curve number, and an initial abstraction coefficient for the SCS curve number.

Water is added to the soil profile (Step 12), filling each layer to field capacity; excess water moves to the next soil layer.

Deep drainage (Step 13) occurs whenever all soil layers are filled to field capacity, and this water is lost from the modeled system.

Maximal potential evapotranspiration (EO) is calculated with an evapotranspiration equation (Step 2), developed for alfalfa with water non-limiting (Jensen and Haise 1963). Since range grasses transpire less freely than alfalfa, this value is reduced by a crop coefficient (CROPCO); the new value represents potential evapotranspiration from rangeland (PET) (Step 4). PET = EO * CROPCO. The crop coefficient was set equal to 0.85, calculated from lysimeter data taken in eastern Montana rangelands (Wight and Neff 1983).

Potential evapotranspiration from rangeland is then partitioned into potential transpiration (PTRAN) and potential evaporation (PEVAP) (Step 5).

Potential transpiration (PTRAN) is assumed to be dependent on both potential evapotranspirative demand and leaf area (Step 6). Potential transpiration is set at half of potential evapotranspiration by a transpiration coefficient (TRANCO). The value of TRANCO (50%) was determined for a rangeland site in eastern Montana (Wight and Neff 1983); sensitivity analyses showed that yield predictions were not sensitive to this parameter (Wight and Neff 1983). The model estimates leaf area from a "relative growth curve" (RGC) (Step 3). This curve represents the percent of maximum leaf area over time and thus limits potential transpiration until peak standing crop occurs (Figure 3). After peak standing crop, the relative growth value (percent maximum leaf area) decreases until the end of the growing season. PTRAN = PET * TRANCO * RGC.

Actual transpiration (ATRAN) is calculated from the potential transpiration value and draws water from each soil layer consecutively downward, until demand is met (Step 15). Potential transpiration is limited or reduced by three factors in the calculation of ATRAN: by a soil water value below which water is unavailable (UNASM), by soil water availability, and by a root activity function. The first limit, the lower bound of plant available water, is established by an input parameter for each layer (UNASM(i)), which corresponds to the permanent wilt soil water percentage for that layer. The availability of soil water, or the percentage available soil water, is the second limit to transpiration. The percentage available soil water is the ratio between available soil water and the available soil water capacity. (SOILM(i) - UNASM(i))/(MHC(i) - UNASM(i)). Available soil water is equal to the difference between the current soil water value, SOILM(i), and the UNASM(i) value. The available soil water capacity is the difference between the water content at field capacity, MHC(i), and the water content at the UNASM(i) value. Thus, transpiration occurs at a maximal rate only when the layer is at field capacity. The third limit to transpiration, the root activity function, is

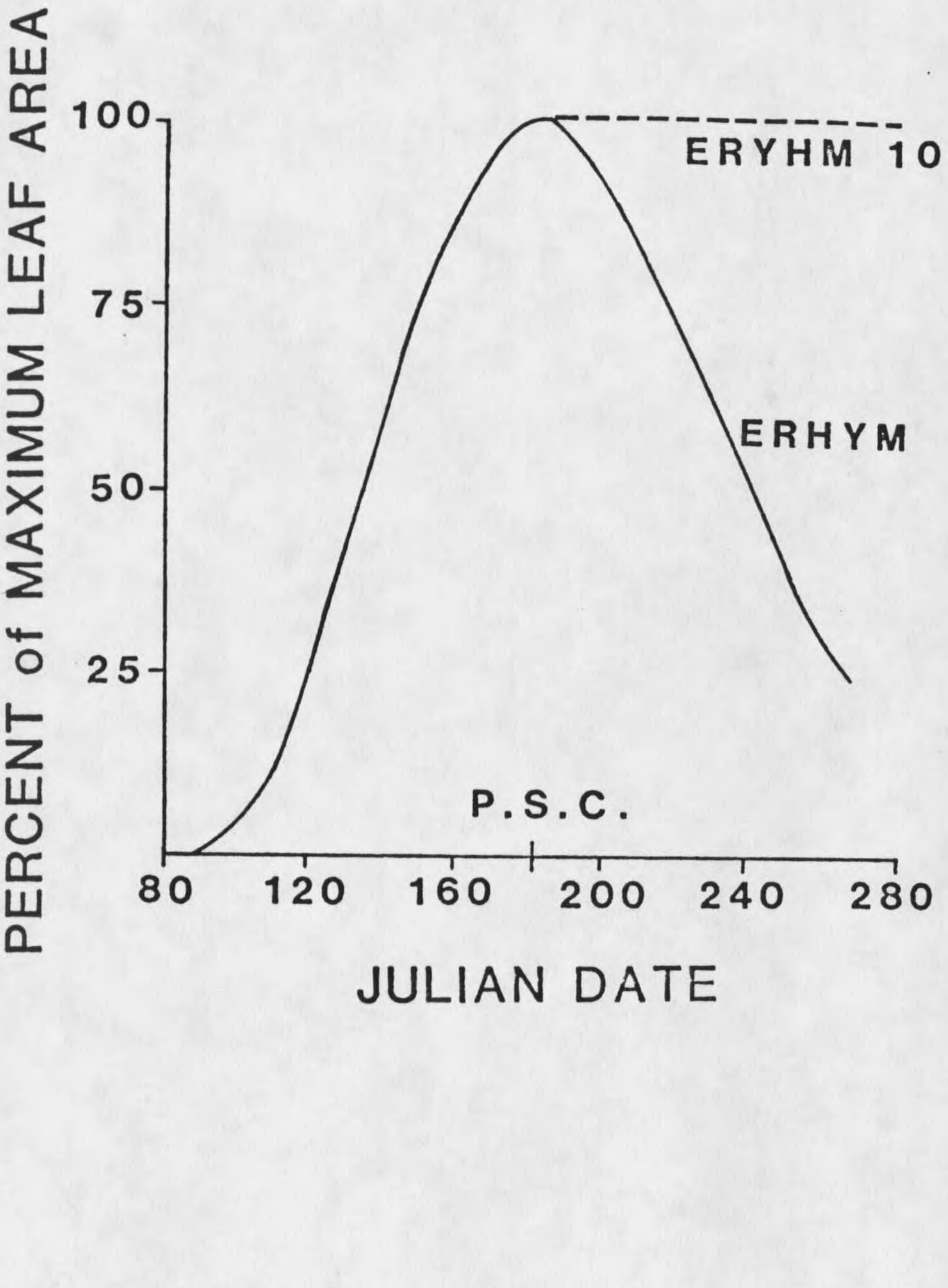

Figure 3. Relative growth curves. Solid line represents ERHYM relative growth curve. Dashed line represents a modification which allows plants to remain at maximum "leaf area index" after peak standing crop (P.S.C.) occurs, thereby maintaining potential transpiration late in the growing season.

calculated from seasonal soil temperature curves (de Jong 1978) and soil temperature-root activity relationships developed by de Jong (1974) for Saskatchewan, Canada. Overall:

ATRAN = PTRAN * (SOILM(i) - UNASM(i))/(MHC(i) - UNASM(i)) * ROOTF

Potential evaporation (PEVAP) is the remaining portion (50%) of potential evapotranspiration not allocated to potential transpiration (PTRAN) (Step 7). PEVAP = PET - PTRAN = 0.5 * PET.

Potential evaporative demand is reduced by a factor of the number of days since the soil was last wet (t) (Step 9). In the field, this reduction occurs as water drains to deeper soil layers, which are less exposed to drying air. AEVAP = PEVAP * $t^{-1/2}$.

Actual evaporation (AEVAP) is calculated from the potential evaporation value and draws water from soil layers consecutively. Water loss is limited by depth, and by an "air dry" value for each soil layer. Maximum depth from which soil evaporation can remove water is set at 30 cm. The air dry value (AIRDRY) for the soil layers is an input parameter.

The yield index calculated by the model is an estimate of plant growth for current climatic conditions and site parameters, and is expressed as a percent of site potential yield (Step 18). This cumulative index equals the ratio of actual transpiration (CTATRN) (Step 16) to potential transpiration (CTPTRN) (Step 17). The index, or predicted total plant yield, is calculated on the date peak standing crop occurs, an input parameter. The product of site potential yield (kg/ha) and the yield index (%) therefore provides an estimate of cumulative production.

Model Testing and Fitting

The ERHYM model was tested by running the model with measured state and driving variables, and comparing simulated soil water and yield values with those observed in the field. Input data included climatic records and site characteristics described below. Testing and fitting data included five years (1977-1981) of soil water and yield measurements gathered from control (unirrigated) plots at the Miles City sites. These five years include a very wet year (1978) and a very dry year (1980); thus, the simulations represented the range of likely system response.

The soil parameters required by the model were assigned on the basis of field observations made in the period 1977-1981. Four soil layers (Figure 1) were used in all simulations. The soil layers were chosen primarily for their compatibility with available soil water data (gypsum blocks), and secondarily, to approximate the natural layers found at the two experimental sites in eastern Montana. A thin soil layer, 0 to 10 cm, lies above a 10 to 30 cm layer, a 30 to 50 cm layer, and a layer extending from 50 to 100 cm. Values for percent water at field capacity and for percent water when the soil was "air dry", were estimated for each layer by the highest and lowest soil water percentages, respectively, which were observed in the five year field study (Weaver et al. 1981). Estimates of percent unavailable water were traditional permanent wilt soil water percentages, i.e., the -1.5 MPa pressure membrane values for each soil layer (Slatyer 1967).

Plant parameters required by the model include a definition of the growing season and the transpiration coefficient. The growing season defined for the model extended from the first of April through the first of October. Date of peak standing crop was set as 1 July (Julian day 182), on the basis of five years of monthly clip data at the two field sites. The transpiration coefficient was set equal to 0.85, a value established from lysimeter data in eastern Montana (Wight and Hanks 1981).

To insure that the model "fit" the field data, instantaneous model predictions of soil water and a cumulative prediction of plant growth were compared to field data. Predictions of soil water were compared to values measured in the field; this comparison simultaneously tested both water addition and water removal functions of ERHYM. Plant growth predictions were compared to standing crop measures, to test the model's plant growth functions. While quantitative field measures of separate water addition and removal functions were not available in all cases, correspondence of simulated values to field conditions demonstrated the model's predictive capacity.

The major water addition and water removal functions in ERHYM are precipitation, runoff, deep drainage, and evapotranspiration. Precipitation is the only process which adds water to the system; water is removed by runoff, deep drainage, and evapotranspiration, i.e. evaporation and transpiration. Comparison of simulated and field-measured values for each of these functions, and analysis of errors in each, provides a measure of model accuracy.

Quantitative measures of precipitation were available for both sites. Rainfall was measured daily throughout each growing season, 1977 through 1981.

Runoff was not observed in five years of data collection at the field sites, either as water flows or as debris terraces (personal communication Weaver). Since runoff was not observed in a very wet year (1978) or in any years on heavily irrigated plots (25 mm water per week), this function was set to zero. Although runoff may occur during heavy showers, resultant errors will be small since these events are rare in eastern Montana. In the event of a heavy shower, the model will, however, overestimate soil water. Errors due to runoff occurrence were assumed to be negligible.

No field measurements of deep drainage were made. If plant roots are present at depths greater than one meter, which was the bottom of the modeled profile, the model may underestimate available water. Deep drainage was observed in some of the simulations, but the conditions which caused deep drainage to occur also occurred during growing seasons when the plants were not greatly water-limited. Therefore, errors due to deep drainage were also assumed to be negligible.

No field measurements of evapotranspiration were available to compare with the model's evapotranspiration predictions. However, Wight and Hanks (1981) tested ERHYM's evapotranspiration functions by comparing model values to lysimeter values and to water-balance calculations, and found very good agreement. Lysimeter comparisons (water non-limiting), showed average model evapotranspiration values to be slightly low, due to early season underestimates (Wight and Hanks 1981). Comparison of three seasons of water balance calculations with field data yielded r^2 values of .97 (1977), .98 (1978), and .99 (1979) (Wight et al. 1983).

Plant yield can be used as a further corroboration of evaporation and transpiration functions. The model assumes that the plant yield index, the ratio of actual transpiration to potential transpiration, (both cumulative), is equal to a ratio of actual yield to site potential yield. Therefore, if the model yield index corresponds to measured biomass, then the model yield prediction corroborates both the model's transpiration and evaporation estimates.

Variations of the relationship between yield and transpiration or evapotranspiration have been used to predict yield for many crops (reviewed by Briggs and Shantz 1913, De Wit 1958, Vaux and Pruitt 1983, and Hanks and Rasmussen 1982). This relationship has proven useful in predicting both grain and dry matter yields (including above- and below-ground yields) for crops such as corn, spring and winter wheat, sorghum, and cotton.

The yield-transpiration relationship has been less studied in native plant communities. Wight and Hanks (1981) found a high correlation, (r^2 value of .74), when comparing field-measured yield and model-predicted yield for native range in eastern Montana; similarly, de Jong and MacDonald (1975) report very high correlation (r=.99) between evapotranspiration and range herbage yields in Canada.

Field measurements of plant biomass were compared to the model yield index, which is expressed as percent of site potential yield.

The largest observed production measure (1978 fall wet plot) (Weaver 1981) was used as an estimate of site potential yield.

Model Modification

Preliminary simulations of unirrigated plot data (1977-1981) showed deep soil layers drying too slowly late in the season. Minor changes in the model were therefore necessary, to better simulate the field-measured soil water data.

Three changes were made in the model to correct its late season underestimate of evapotranspiration. These changes increased transpiration by preventing spring and fall soil temperature limitation of root activity, by maintaining a large transpiration surface (LAI) after peak standing crop, and by increasing the availability of soil water to transpiration.

The root activity function was modified to prevent the original model's possible limitation of root water uptake in the spring and fall (ROOTF=1.0). The function used by Wight and Hanks (1981) was based on soil temperature data from Saskatchewan, Canada. The modification in duration of root activity was based on the assumption that soil temperature did not limit root activity during the growing season (1 April to 1 October) at the more southerly Miles City sites.

The plants' relative growth curve was modified to allow maximum potential transpiration (potential growth) after peak standing crop (see Figure 3). This preserves a large leaf area for the plants, through the end of the growing season, and agrees with the observed maintenance of green leaf area (Newbauer 1985). In contrast, the original relative growth curve (leaf area) decreases from the day of peak standing crop through the end of the growing season (see Figure 3).

The transpiration response function was modified so that soil water was freely used until available water fell to fifty percent of available water capacity and then became available as a linear function of soil water (Figure 4). In contrast, the original transpiration response function shows a linear decline in the availability of soil water, throughout its range. The water characteristic curves of relatively clay-poor soils (Slatyer 1967), such as those of the Miles City sites, suggest water release characteristics similar to this modified function.

Soil water predictions made with the modified model in "fitting simulations" (non-irrigated plots, 1977-1981) compared favorably, but not perfectly, with gypsum block soil water data from both sites (Figure 5,6). Since differences between predicted and observed soil water may be no more due to model inaccuracies than to measurement inaccuracies, the assumption was made that the model predicted soil water realistically for unirrigated plots.

Gypsum block data is an imperfect estimate of water content. The estimate is affected by hysteresis (Taylor and Ashcroft 1972), which contributes to measurement inaccuracies and regressions used for block calibration do not take hysteresis into account (Appendix A). Since the mean block reading is a point estimate of water content in a relatively thick layer of soil, it is not as sensitive to light precipitation events (wetting) as is the model. For example, the

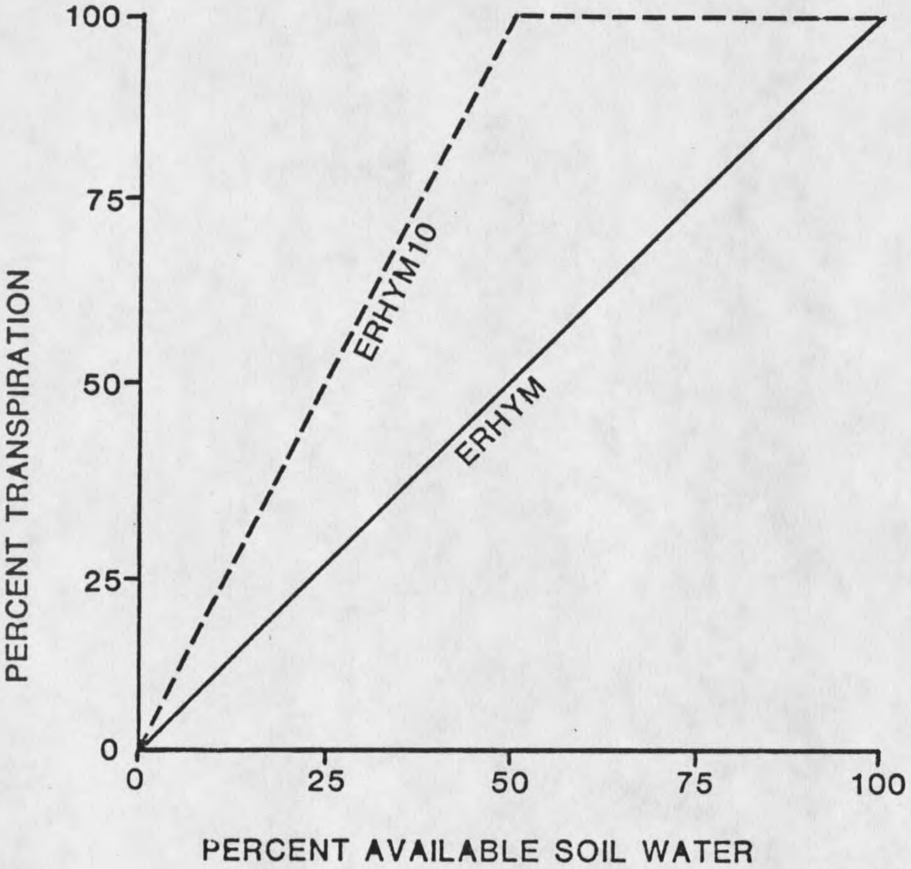

Figure 4. Transpiration response function. The solid line represents the original transpiration response function (ERHYM). Dashed line represents modification of the function (ERHYM10); when soil layer is drier than 50% of plant available water capacity, transpiration is limited by the percentage calculated with this function.