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Use of Soil Moisture Information in Crop Yield Models

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USE OF SOIL MOISTURE INFORMATION IN YIELD MODELS

NASA/JSC Report

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Executive Summary

This report considers (1) the state of the art in the yield prediction capabilities, (2) the sensitivity of yield models to soil moisture by growth stage, (3) the need for soil moisture information in order to achieve improvement in yield prediction, and (4) the characteristics of a system for obtaining soil moisture information.

Soil water models and crop yield models are reviewed. Soil water models are incorporated into several existing yield models and could be incorporated into others since the inputs to the simpler soil water balance models are available. This is not to say, that in all cases, will one find an improvement in yield prediction. In general, when one is considering a physiological or process - orientated model, improving the soil water balance should improve yield prediction. However, under conditions when soil water is not a limiting factor in crop yield, models that do not contain a soil water balance may perform as well as those that do. Consequently, improvements in predicting crop yields from physiologically-based models can be expected as the effects of water stress are determined and incorporated. It is evident that soil water balance modeling has progressed ahead of physiological modeling. Improvements in assessing crop response to its environment will improve yield estimates from physiological models.

It is recommended that further studies be made to evaluate the usefulness of soil moisture information in yield models. Soil moisture information and specific yield models should be evaluated together. In addition, an array of soil water balance models, varying in complexity, should be studied, using existing data, in predicting soil moisture profiles for several soils and climates. There may be instances where additional data may be required for complete analyses.

Further studies are recommended to determine the depth of the surface soil layer required for characterization to provide useful information in soil water balance and in yield modeling.

The committee recommends specific characteristics of a system for obtaining soil moisture information relative to yield modeling. The most important of these is a sampling frequency of 3 to 5 days to assess crop cover and/or leaf area.

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1.0 Introduction

It is axiomatic that soil water deficit limits crop yields in many areas of the world. The agronomic literature is replete with studies showing the effect of water deficit on yield. Many of these studies have been utilized to describe the sensitive stages of growth for various crops (Salter and Goode, 1967). Hsiao (1973) has reviewed the effect of water deficit on many physiological processes. Cell growth and wall synthesis appear to be the most sensitive while respiration and photosynthesis are sensitive to a lesser degree. Therefore, Hsiao (1973) notes that dry matter production may be affected even though the water deficit does not reduce assimilation. It is not completely understood how physiological processes (cell growth, wall synthesis, protein synthesis, protochlorophyll formation, proline accumulation, photosynthesis, respiration, etc.) interact and how they are integrated to cause changes in yield.

Plant processes are dependent on the water status of their tissue. The water status (or turgor pressure) of a plant is dependent to a large degree upon the soil water content in the root zone and the atmospheric demand. The atmosphere places an evaporative demand upon the plant and the roots absorb water from the soil-water reservoir. When the reservoir becomes depleted,e.g. from lack of precipitation or irrigation, the roots cannot absorb water at a rate to meet the demand and the plant loses turgor. Subsequently,physiological and metabolic processes are affected. One of the major processes affected is photosynthesis which supplies photosynthate to the growing organs.

The effect of water deficit on yield is dependent on the developmental stages at which the deficit occurs and the sensitivity to deficit in various developmental stages. Landsberg (1977) defines plant development as the sequence of ontogenetic events involving both growth and differentiation leading to changes in function and morphology. The relationship of water deficit and yield is further complicated by the adaptive capability of some plants. Plants are very dynamic and are modulated by continuous interactions with the environment. The linking of biochemical processes to physiological changes and then to whole plant and community effects is very difficult. Therefore, in the short term, empirical relationships that have a physiological basis will have an important role in modeling efforts.

While water deficits play a major role in affecting large area production, it is not the only effect. Disease, fertility, crop management, insects and epidsodal events can seriously alter yield. These yield deterrents need to be removed or isolated when using a particular data set to develop certain aspects of a model or test for sensitivity. If yield is reduced by disease, it does not improve the model estimates to know soil moisture more accurately.

In general,the scientific community would support the view that soil moisture (amount and depletion) and plant available water throughout the growing season adds information about yield response that is not available from meteorological data alone; however, the incremental improvement in yield prediction obtainable has not been assessed in direct comparisons with and without such data.

To aid in this assessment, the Evapotranspiration Laboratory at Kansas State University, under a contract (NAS-9-14899) from NASA Johnson Space Center (JSC), gathered a working group of recognized scientists in the area of remote sensing, soil moisture modeling, and crop yield modeling. The working group considered (1) the state of the art in yield prediction capabilities, (2) the sensitivity of yield models to soil moisture by growth stage, (3) the need for soil moisture information in order to achieve improvement in yield prediction, and (4) the characteristics of a system for obtaining soil moisture information (temporal resolution, spatial resolution, time of day, grid size).

This report is the result of the workshop held at Kansas State University on January 24 and 25, 1980.

2.0 Literature Review

Yield models usually possess a soil-water term or a surrogate relationship. In some models, it is precipitation or antecedent precipitation which is used to simulate the storage effect of the soil profile. In others it is a water balance approach. The basic components to a soil-water balance model are (1) the additions of water (precipitation/irrigation, and upward or lateral movement), (2) the losses of water (evapotranspiration, sublimation, surface runoff, groundwater flow, and deep percolation), and (3) the change in the storage of the plant available or extractable water content. The components are not independent but are interrelated. For example, amount of runoff depends partially on the rainfall intensity, hydraulic properties of the soil, and surface water content. Evapotranspiration is estimated from knowledge of plant available water and soil water content.

In general, the redistribution of water in a homogenous soil profile is well-understood; however, the models are relatively complex and require several soil-water parameters (liquid and vapor) that are usually not readily available (Nimah and Hanks, 1973). In addition, few soils have a homogenous profile. Therefore, in many soil moisture models, redistribution is simulated in a simple and empirical manner. Several yield models, which have a soil water balance, treat redistribution empirically and assume downward flow but not upward flow (Hanks, 1974; Hodges and Kanemasu, 1977; and Arkin et al., 1976). To account for upward movement, water content-matric potential and water content-hydraulic conductivity relationships and the depth of the root zone during crop development are required. The soil water balance model of Saxton et al.(1974) uses that approach as does the yield model of Childs et al. (1977). Areas that have a near surface water table or a fluctuating water table or salinity add further complications to any soil moisture model. The soil moisture model of Stuff and Dale (1978) and the yield models of Holt et al. (1964) and Reetz (1976) treat this situation.

The processes in which the soil reservoir loses water are also relatively well-defined. Evapotranspiration is largely an energy driven process; therefore, solar radiation and temperature are primary inputs. The Penman-type equations also require vapor pressure and windspeed (Penman, 1948). Runoff can be a major term in the daily water balance. For example, if the surface soil is near saturation or "puddled" and/or the rainfall intensity is high, a significant amount of precipitation can be surface runoff. Obviously, surface conditions such as mulch, slope, soil type, soil structural stability, vegetation, and tillage practices can also affect runoff amounts.

The water storage capacity of a soil that is extractable by the plant (maximum extractable or available water) is often not precisely known. Soil water storage capacity is influenced by soil-and plant-root extraction factors. This should be determined in the field as the soil water content when the profile is filled and allowed to drain minus the soil water content when the plants are severely wilted (plants do not regain turgor within 24 hours). Historically, these limits have been defined as field capacity and permanent wilting point. Field capacity and permanent wilting point have often been defined as the water content at -1/3 bars and -15 bars soil matric water potential, respectively. Experience has shown that these limits are at best only a rough approximation. One problem is that the amount of available water is dependent upon the crop rooting depth and content. It is obvious that a plant with a deeper rooting depth will have more available water than a shallow rooting plant. Therefore, it is customary for a soil moisture model to incorporate the dynamics of root extension. These dynamics are usually empirical because the growth and activity of root systems are difficult to observe and are affected by root and above ground plant interactions with specific environments.

For example, a recent study by Stewart *et al.* (1977) has shown corn grown at Davis, California, extracted about 40 cm of water to a depth of 2.5 m whereas the same crop grown on similar soils at Logan, Utah, and Ft. Collins, Colorado, extracted about 23 cm of water to a depth of only 1.4 m.

Another problem is caused by the influence of soil structure on the soil water content - matric potential relation. Under field conditions the matric potential at "field capacity" may be about -0.08 to -0.2 bars compared to the -0.33 bars required to dry a disturbed sample of the same soil to the same water content.

2.1 Comparisons of Soil Water Balance Models

Within soil water balance models, soil profiles are usually divided into discrete layers of either uniform or variable thickness to represent the soil to below the total rooting depth. Each layer is assumed to have uniform moisture content and to possess some portion of the total plant roots for water extraction purposes. The infiltration and redistribution of water throughout the layered soil profile is often treated in two rather different procedures.

The more simple of the two water flow methods is to define a water content at which that layer could hold no additional water and subsequent infiltration would be "cascaded", or freely transmitted by gravity to the next lower layer or out of the profile if it was the lower most layer. The upper limit of water for each layer is usually set near the field capacity. Field capacity is usually defined as that water content to which that soil would readily drain after being thoroughly wetted or it is approximately the water content at which the unsaturated conductivity (or diffusivity) begins a pronounced increase as it is wetted. This method is very easy to program and efficient to calculate. It does not allow for any upward movement of water and no time distribution of water movement unless that is an added feature. The effects of restricting layers or water tables are not readily represented. Definitional data for this method can usually be estimated from soil descriptions, but are best estimated from field measurements of soil water content under wet and dry conditions.

The second method is to treat the layered soil profile by a solution of the Darcy unsaturated flow equation in which each layer is assumed to be uniform in moisture content, capillary pressure, and unsaturated conductivity. Mathematical solutions vary from simple finite differences with large time steps to finite element with near-analytical results. This treatment of water flow can be used to represent nearly all situations including upward or downward flows between layers, widely varying characteristics within the profile, time distribution of infiltration and redistribution among the layers, water tables, and plant water withdrawal. The soil-water-matric potential relationships for each layer are quite difficult to obtain either by measurement or from literature, and the computational requirements are several times that of the cascading procedure and can become exorbitant if many thin layers and short time increments are used. However, if even approximately correct characteristic curves are assigned, the results are quite realistic for a wide variety of cases. As with the simpler models, these procedures also require extraction procedures that are rather crude.

The choice of which soil water movement calculation to employ depends on the accuracy and precision required, computational time allowed, available data, spatial variability, and location of water table (if present). For a readily drained soil where withdrawal of water by the plant dominates the water profile development and casual accuracy is required, the cascading principle would be adequate. Other situations (e.g. upward flow, salinity, short time information, etc.) usually require the application of some form of Darcian representation. There are some generalized methods of estimating the soil-water-matric potential relationships from soil profile descriptions, and simplified finite difference solutions with stability criteria can keep computations minimized and practical on modern computers.

One of our interests (in soil moisture modeling) is to account for the effect of water deficit on plant transpiration and soil surface evaporation. As the plant undergoes water deficit, stomata close and transpiration is reduced. The question then is at what soil moisture and evaporative demand condition does this occur? As water stress occurs, canopy geometry changes and that may influence the partitioning of energy between evaporation and transpiration. A slowly developing deficit (e.g. a crop on a fine-textured soil or restricted root penetration) may cause a decline or lessening in leaf area which would also affect evapotranspiration. Many models (Hanks, 1974; Hodges and Kanemasu, 1977) represent the plant response to soil moisture by a linear decline below a particular soil moisture availability (e.g. 50% or 35% availability) and assume no effect above that level or to 100% (field capacity). Others (Childs and Hanks, 1975) take into account the combined affect of atmospheric demand, root distribution, and soil water flow characteristics to determine the point where transpiration is less than potential.

2.2 Yield and Water Use Relationships

Several studies have shown a close relation between yield and water use (transpiration)(Briggs and Shantz, 1917; de Wit, 1958; Hanks, 1974; and Slabbers *et al.*, 1979). Other studies have also shown a good relation of yield to evapotranspiration (ET) (Stewart *et al.*, 1977). It is almost impossible under field conditions to separate evaporation (E) from transpiration (T). In general, the studies indicate that (1) dry matter production and evapotranspiration (ET) are more closely correlated than grain yield and ET, (2) improvements in those correlations are observed when transpiration (estimated) is used instead of ET, (3) incorporating effects of water deficit at critical growth stages may improve the correlations, and (4) economic yield-ET relationships can change from location to location, year to year, crop to crop, and variety to variety (thus site specific).

Equations relating yield to water use are of the form

$$Y = mT/E_o \qquad [1]$$

where T is the transpiration, m is a crop factor and E_o is a climatic factor. Many investigators have used pan evaporation to estimate E_o (de Wit, 1958). Others have suggested a relative humidity function (Arkley, 1963). Transpiration could be estimated from an ET model that estimates T and E separately. Relationships such as [1] provide a linear relationship between yield and T/E_o which is independent of the site or environment. Fischer and Turner (1978) have indicated the "m" value of similar plants (i.e. C_3) are similar provided roots and shoots are included in the dry matter yield. Tanner and Sinclair (1980) have also made similar conclusions.

An alternative to [1] is

$$Y = (Y_m/T_m)T \qquad [1a]$$

where Y_m and T_m are the potential yield and potential transpiration, respectively; however, the potential yield terms must be estimated each year for each location. This method has the advantage of not having to know "m" or "E_o" but requires a knowledge of Y_m. If Y_m is obtained by some experimental means such as a non-stress field (adequate moisture) it would account for many crop and soil management affects that are presently difficult to model (Hanks, 1974). However, this approach is more useful when comparing treatments within a given year.

Stewart et al. (1977) developed the following relationship for dry matter:

$$Y/Y_m = 1 - \beta_o ET_D = 1 - \beta_o + \beta_o ET/ET_{max} \qquad [2]$$

where β_o is the slope of relative yield versus ET_D and ET_{max} is defined as the ET required for Y_{max}; ET_D is given by $1 - ET/ET_{max}$. The value of β_o must be obtained from field measurements. Hanks (1980) suggests that a reasonable value of β_o could be made and large changes in β_o are not observed from year to year. More complicated forms of [2] could be formulated by evaluating ET_D in each growth stage and weighting each growth stage by a factor. The use of [2] also requires estimates of ET_m and Y_m.

It seems reasonable physiologically to weight the normalized transpiration (e.g. T/ET_o) according to growth stages, (i.e. with winter wheat: emergence to jointing (stage 1), jointing to heading (stage 2), and heading to soft dough (stage 3)) and to provide preference to longer time periods within a growth stage. Rasmussen (1979), who allowed for both of those concepts in his winter wheat study, developed the following grain yield-water use equation:

$$Y(kg/ha)=1.92(\Sigma(T/ET_o))_1^{0.172}(\Sigma(T/ET_o))_2^{0.104}(\Sigma(T/ET_o))_3^{0.646} \qquad [3]$$

where the subscripts refer to the growth stages indicated above. Daily T/ET_o ratios are summed during each of the stages. ET_o is estimated by the Priestley-Taylor equation. The maximum T/ET_o summation would be the total number of days in each growth period. Equation [3] has the advantage that neither the potential yield nor the "m" factor needs to be known. In 95 observations of three sites over three years, Rasmussen (1979) reported a correlation coefficient (r) of 0.68. Better results were obtained with a data subset in which water was the primary yield-limiting factor ($r^2 = 0.91$).

2.3 Yield-Climate Models That Do Not Use a Soil Moisture Balance.

The Thompson-type models are representative of these models. Other models are given in Appendix A (Thompson 1969 a, b, 1970). The major attractiveness of the Thompson-type models is the availability of input data, primarily temperature and rainfall. Yields are predicted for a large region, crop reporting district or state. Technological trend in the model is a major influence in predicting yields over time.

The Leeper _et_ _al_. (1974 a, b) model is another example of this type of model. This particular model requires measured soil moisture at planting in addition to precipitation and temperature. Runge and Benci (1975) ran the Leeper _et_ _al_. (1974 a,b) model from 1901 to 1968 for several mid-western areas. Although they never compared the model predictions to actual yields, the model did show depressions in yields during the 1930's and in the early 1950's which corresponds with known periods of low yields. Model examination and sensitivity analysis by Huda (1978) showed that the model behaves in a consistent manner. Work by Nelson and Dale (1978) showed that the Leeper model performed as well as several other regression models for two Indiana counties. These regression models were derived from a historical data series for those counties. Keener _et_ _al_. (1979) found that the Leeper model could be used for state-wide yield prediction for Iowa, Illinois and Indiana but not for Missouri yield predictions. Of the regression type models, the Leeper model has received the most independent testing.

The Cate-Phinney spring wheat yield model is a unique statistical model in that the Liebig Law of the Minimum was used to estimate coefficients rather than regression. The basic model proposed by Cate et al. (1979) as modified by Phinney et al. (1980) incorporates native soil fertility, applied nitrogen, percent fallow, varietal differences and four weather related variables. The weather related variables are averaged over key growth stages based on a phenology submodel. Temperature stress during grain filling and nutrient/water stress during three different stages are considered. The dominant terms in the model are plant available nitrogen estimates calculated from total nitrogen, and relative available water. The relative available water term is based on the difference between total precipitation and estimated total pan evaporation for a given growth stage. An empirical estimator of pan evaporation developed by the authors was used.

The Cate-Phinney model was evaluated by the authors for large area applications (Phinney et al., 1980) in the U.S. spring wheat region. Based on a ten year test over an independent data set, the model was found to be significantly better than the spring wheat models used operationally during the Large Area Crop Inventory Experiment (Strommen et al., 1979). The authors concluded that incorporation of a budget type soil moisture submodel could be expected to show additional improvement in model performance.

2.4 Yield-Climate Models That Use a Soil Moisture Balance.

Dale and Hodges (1975) propose expressing the environment as a single composite index (ECG). This index is a summation of daily indices computed from solar radiation, leaf area index, evapotranspiration and potential evapotranspiration. Yield was obtained from a regression equation of nitrogen and ECG.

Feyerherm (1979) developed a regression equation relating daily weather parameters to plant response at various growth stages. The ET/PET ratio is one of the primary terms and soil moisture affects ET. A soil water balance is used in the model (Baier and Robertson, 1966).

Hodges and Kanemasu (1977) developed a growth model for winter wheat. The inputs are daily solar radiation, maximum temperature, minimum temperature, precipitation, and leaf area index (LAI). The model estimates evaporation and transpiration, separately, then uses a soil water balance to estimate the soil moisture profile (Kanemasu et al., 1976). Phenology of the crop is predicted by a modified biometeorological time scale (Feyerherm and Paulsen, 1976). Daily net photosynthesis is estimated and total dry weight is predicted each day. Photosynthesis is estimated from solar radiation and LAI. Daily LAI is simulated from frequent ground observations (Pollock and Kanemasu, 1979). Grain yields are predicted from kernel numbers per unit area (KNO) and kernel weight (KW). KNO is estimated from total dry matter at heading and KW is estimated by photosynthesis during grain-filling.

Hanks and Puckridge (1980) have proposed a spring wheat growth model. The inputs are daily potential E_o, and precipitation (or irrigation). The "green" LAI is predicted from a combined time-potential E_o relation, and crop phenology. The predicted values of LAI are used to predict daily dry matter accumulation from estimated net photosynthesis. Grain yields were not predicted because the data base tested had an almost uniform harvest index. Transpiration is estimated as a function of LAI as is soil evaporation. The soil water budget is handled similar to Hanks (1974). This model accounts for planting density and predicts influence of date of planting as well as soil water storage effects.

The Purdue Corn Simulator (PCS) is a carbon-balance model that predicts corn growth and development on a daily (or hourly) basis throughout the growing season (Reetz, 1976). Relationships of various environmental parameters to physiological processes of photosynthesis, respiration, translocation and growth are expressed in empirical equations derived from detailed growth analysis work and literature values. The PCS model incorporates the concepts of the SIMBAL model (Stuff, 1975) as the basis for its water relations subroutines. Plant available soil moisture determined daily by SIMBAL is used along with environmental data to estimate water potential values for leaves, stalks, roots, and ears. Water potential values at each time step then influence physiological rates.

SIMAIZ is a corn yield simulation model developed by Duncan (1975) at the University of Kentucky. A soil water balance using Ritchie's (1972) approach is obtained each day. The program accumulates daily growing degree days. Daily photosynthate is calculated from development, intercepted radiation, temperature and soil moisture. If sink size is not limiting, grain yield is determined by photosynthate produced during grain filling plus translocation. Similar simulation models have been developed for other crops e.g. soybean, peanuts, and alfalfa.

EarthSat developed a wheat model (EarthSat, 1976) which uses a soil-water balance to estimate the soil moisture in the root zone (Baier and

Robertson, 1966). Evapotranspiration (ET) is reduced when the soil moisture level declines. The ratio of ET to potential evapotranspiration (PET) is used to quantify stress = 1 - ET/PET where PET is estimated by the Penman equation, (Penman, 1948). The effect of stress on yield is weighted by the growth stage.

Saxton and Bluhm (1979) used nearly the same approach as EarthSat. They defined stress the same but obtained ET/PET from a crop cover curve, pan evaporation and a soil water balance model. A water stress index (WSI) was obtained by weighting the stress with a susceptibility factor. WSI was then related to grain yield; however, that relationship did not appear unique but varied with location. Better correlations were obtained when water became limiting to yield.

Childs _et al._ (1977) describe a corn growth model which requires hydraulic conductivity and matric potential characteristics of the soil (after Childs and Hanks, 1975), minimum leaf water potential, root distribution and growth, phenology information, precipitation, solar radiation, maximum and minimum temperature, leaf area index, and potential evapotranspiration. Water flow in the soil profile is simulated. Photosynthesis and respiration are estimated from leaf water potential and solar radiation. Leaf area is generated by the model as is the ear growth. After tasselling, all photosynthate is partitioned to the ear.

Arkin _et al._ (1976) and Vanderlip and Arkin (1977) present a sorghum growth and yield model. That model simulates the leaf growth, light interception and photosynthesis of a sorghum canopy. Soil moisture was determined for the total root zone (single layer model) by a soil moisture balance. Plant inputs are total number of leaves produced and maximum leaf area of each leaf, plant population and row width. Climatic data required are solar radiation, maximum and minimum temperature, and precipitation. Hodges et al. (1979) developed a sorghum yield model similar to Arkin et al. (1976); however, the leaf area is not simulated by the model but is an input.

Baker et al. (1975) developed a detailed simulation model for cotton (SIMCOT II). Plant growth, morphogenesis, photosynthesis, respiration, nitrogen metabolism, etc., are simulated each day. Carbohydrate, soil water and nitrogen balances are developed for the plant which require several plant growth factors. This model is probably the most complex of current yield models.

2.5 Model Tests and Validation

The regression-type models usually have a large data base with which to use in their development, testing and validation. These models perform relatively well in predicting yields for large regions or areas. However, there is some concern about their reliability on unusually high or low yielding years. These models have been developed and tested on several crops and in many locations.

The more mechanistic or process-oriented models require more data (climatic, crop and soil information); therefore, there are fewer data sets for development and testing. These models attempt to simulate processes as well as predict yields on a field by field basis. To assess the yield of a large region, a sampling procedure could be developed in lieu of a wall to wall coverage. These models are in various stages of development and testing; however, testing and validation of these models are lagging behind the regression-type models. Usually the regression-type models have the advantage of being based on past historical data so they will predict results similar to past events. They tend not to predict unusual years well.

3.0 Comparative Tests of Yield Models Incorporating Appropriate Meteorological Data with Soil Moisture Estimates Versus Models Using Only the Observations Themselves.

Some tests have been done comparing the accuracy of yield predictions from models including both meteorological data and soil moisture estimates versus models using meteorological observations alone (Nelson and Dale, 1978; Hildreth, 1978; Lewin and Lomas, 1974; Baier and Robertson, 1968).

Nelson and Dale (1978) tested versions of four statistical regression models for corn yield predictions: the 1) Thompson and 2) modified Thompson approaches, the 3) Leeper _et al_. (1974 a, b), and The Energy Crop Growth (ECG) (Dale and Hodges, 1975) models - for their reliability in yield prediction. The Leeper _et al_. (1974 a, b) model, the modified Thompson approach and The Energy Crop Growth model differed little among themselves, but were found superior to the Thompson approach in predicting corn yields.

Thomas _et al_. (1962) used regression techniques to study the effect of soil moisture supply at seeding and seasonal precipitation on spring wheat yields in South Dakota, North Dakota, and Montana. They found that seasonal precipitation explained more of the variability in yield than soil moisture at planting and the combined information had the lowest standard error of the estimate. Each location had a different regression equation.

Lewin and Lomas (1974) analyzed rainfall and wheat yields by three different statistical methods (multiple regression, principal components, and Fisher's method), as well as by means of a simple soil moisture simulation technique. Both the statistical methods and the simulation model give good results in the arid zone, accounting in all cases for more than 70% of the yield variations. However, in areas of higher rainfall the soil moisture simulation model outperformed the statistical models, although less of the yield variation was accounted for in each case (50% and 30% , respectively), than in arid zone.

Pitter (1977) obtained significant improvements in wheat yield prediction with a soil moisture at sowing parameter included in the model. Bridge's (1976) results reinforce the findings of other research (Baier and Robertson, 1968; Albrecht, 1971; Baier, 1973) that demonstrate the superior association between wheat yield and parameters derived with crop water budget models utilizing soil moisture as opposed to simple energy and moisture parameters such as mean temperature and precipitation. Bridge derived variables for linear regression on wheat yield using computed PET, ET, surplus water, and other soil moisture related variables including a root growth function.

Baier and Robertson (1968) compared the yield estimates of four yield-weather models by simple correlation between observed and estimated yields of Marquis wheat from 39 plantings from 1953-1957 in Canada. The variables and models used were mean values during each of five phenological growth stages of maximum temperature, minimum temperature, and soil moisture, and rainfall totals for each phenological period. The best estimator of yields was the soil moisture model, though it was not significantly different from the minimum temperature model, which was second.

Feyerherm (1979) developed models to predict large-area wheat yield from reported-weather and related-agronomic data. The models were globally applicable except for minor adjustments to correct for local conditions. They were built to respond to both abrupt year-to-year changes due to environmental fluctuations (weather, diseases, etc.) and long-term shifts due to technological improvements through added nutrients, genetic changes (new cultivars), weed and pest control, irrigation, and other cultural practices. Through use of a soil water balance model, daily evapotranspiration (ET) was simulated, and accumulated over simulated phases of a crop calendar to form predictor variables. This provided an opportunity to develop two model types, one which used some ET variables as predictors (ET models) and another that used precipitation (PR models) instead of a soil water balance.

Feyerherm found that for predicting winter wheat yields: (1) fall precipitation was as good a predictor as fall ET; (2) springtime ET predictors were better than precipitation predictors but early spring precipitation amounts do act as precursors for later moisture-sufficiency conditions expressed by ET variables; and (3) precipitation must be used in the post-heading period to express the deleterious effects of excess moisture.

For goodness-of-fit analysis, Feyerherm found that for estimating plot yields: (1) $R^2 = 0.54$ and 0.48 for winter wheat ET and PR models; respectively, and the corresponding standard errors of estimate (S.E.E.) were 8.5 bu./A and 9.0 bu./A; and (2) $R^2 = 0.65$ and 0.55 for spring wheat ET and PR models; respectively, and the corresponding S.E.E. values were 6.3 bu./A and 7.0 bu./A. For predicted yields of winter wheat on a state-wide basis the root-mean-square errors between model and USDA estimates were less for the ET model than for the PR model for all U.S. Great Plains and Cornbelt states except for Nebraska. Simulated ET values are better predictors of grain yield for winter wheat than precipitation <u>per se</u> both from the standpoint of extendability of a model to foreign areas and accuracy of predictions.

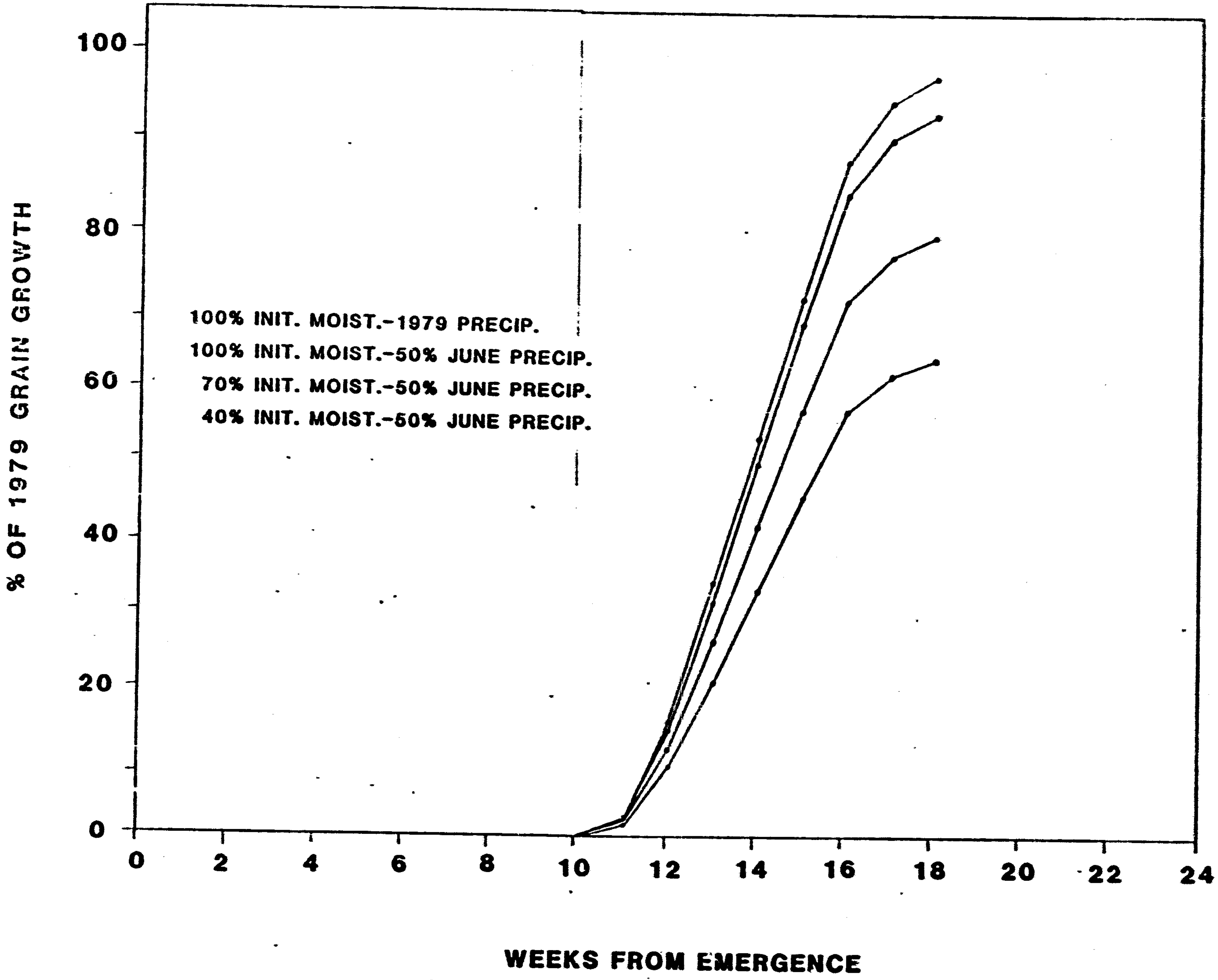
4.0 Sensitivity Analyses of Soil Moisture on Yield

Soil moisture affects crop growth, plant development, and grain yield. Plant responses are an integration of many distinct but interrelated terms. For example, decreased soil moisture will affect plant development and growth; however, the effect of water deficit on grain yield is dependent upon the stage of growth that deficit occurs as well as the severity of the deficit. Because the plant is not seriously affected over a relatively large range of soil water availability and in many regions water limitation is not a chronic problem (Howell *et al.*, 1979), improvements in soil moisture modeling may not reflect any improvement in yield estimation or prediction. On the other hand, a particular weather pattern orchestrating a crop at a particular developmental stage and rainfall event may produce large yield increases. Therefore, attempts to show yield improvements with more accurate simulation of the soil moisture requires simultaneous agronomic and physiological interpretation about whether soil water conditions were or were not yield limiting for a particular data set.

Hildreth (1978) conducted a sensitivity analysis of Feyerherm's (1977) wheat yield models considering planting date, initial available soil moisture, and maximum available soil moisture effects on yield. Simulations of the extremes in actual available soil moisture of 0 (empty) and 10 inches (full) indicate that progressively drier locations become progressively more sensitive to errors in the initial soil moisture amount when calculating yield. It was found that maximum available soil moisture can deviate several inches from the assumed 10 inches before a significant error in yield results. Dry areas were more sensitive to deviations in field capacity and initial soil moisture than were wet areas, emphasizing the importance of accurate data in these areas.

As mentioned previously, some sensitivity analysis of Leeper's model was done by Huda (1978). The purpose of that analysis was to show the affect of an additional inch of water during one week of the ten week period used by the model for different temperatures and different amounts of initial soil moisture. In general, the results were that with high initial soil moisture (10 inches), the addition of one inch of water any one week did not significantly alter model predicted yield for any temperature regime. But with lower initial soil moisture (6 inches), low late season temperatures and increased rainfall resulted in decreased yield while high temperature and increased rainfall resulted in increased yield. A much more extensive sensitivity analysis of the model was made by Klugh (1979). His general conclusions were: 1) the model gives reasonable responses with initial soil moisture between 6-14 inches, 2) temperature establishes yield level and 3) precipitation creates yield changes. He found the model to be extremely sensitive to changes in initial moisture or precipitation. In general, increased water increased yield, and increased temperature decreased yield. If soil moisture values were outside the 6-14 inches range, model yields tend to fluctuate more, depending upon the temperature and precipitation regimes used. Approximately the same change in yield was achieved by an increase in rainfall of 0.1 inch or a decrease in temperature of 1.0°F.

Process-level simulation models (Reetz, 1976) are also very dependent upon good soil moisture input. Incorporating the concepts of the SIMBAL (Stuff, 1975) soil moisture model, the PCS model is especially sensitive to timing of stress relative to stage of crop growth. The following figure shows the impact of reducing rainfall during the growing season. Effects on both vegetative growth and grain development are noted. Since the rain-


100% INIT. MOIST.-1979 PRECIP.
100% INIT. MOIST.-50% JUNE PRECIP.
70% INIT. MOIST.-50% JUNE PRECIP.
40% INIT. MOIST.-50% JUNE PRECIP.
% OF 1979 GRAIN GROWTH
0
20
40
60
80
100
WEEKS FROM EMERGENCE
0
2
4
6
8
10
12
14
16
18
20
22
24

fall reduction was after most vegetative growth was complete, the impact on grain growth was greatest.

5.0 Use of Soil Moisture Profile Measurements in Improving Yield Estimates

Information about the soil moisture profile can be used to check or provide (1) feedback profile information to soil moisture models, (2) revisions in soil-water relationships, (3) initial soil moisture conditions, and (4) estimates of evapotranspiration. Disparity between the model and measured profile may be due to inaccurate estimates of meteorological and hydrological inputs such as precipitation and runoff. The soil moisture model may not be designed to handle conditions such as rough terrain, beds, deep furrows, minimum tillage, large soil cracks, ponding, upward movement of water, fluctuating water table, etc. A soil moisture measurement not only provides a check but can provide initial or update soil moisture conditions. Every model must start with a soil moisture value at each of the depths it is concerned with. Soil-water relationships developed for a particular area or soil unit may be inappropriate and measured profile conditions can permit revisions in these relationships.

On the other hand, because of soil variability, in situ soil moisture measurements may not be useful in assessing the soil moisture status of a field unless they are sufficiently replicated. Therefore, soil moisture profiles may be more realistically modeled than measured but it may be best to use a combination of measured and modeled values. This may be particularly true for large areas.

Direct soil moisture measurements, along with soil-water characteristic data, can be used to estimate the relative transpiration (or evapotranspiration) and growth. If measurements are frequent enough they can be used, together with measurements of precipitation (and irrigation), runoff and deep drainage, to estimate evapotranspiration and thus yield. If runoff and deep drainage are not important, then beginning and ending seasonal measurements may be sufficient.

Where deep drainage and/or runoff is important, more frequent measurements will be needed. This will also be true if the crop under consideration has a sensitive growth stage.

However, the most useful value of measuring soil moisture will probably be to update soil moisture balance models to minimize errors that may have built up. If these errors are found to be small, the water balance simulations can be extrapolated and interpolated more widely. Another related use would be to provide the beginning and ending water contents needed in models.

A further use of soil moisture measurements, for model use, is to provide the data on available soil water and rooting depth characteristics needed by most models. The use of soil moisture measurements alone to predict yields by statistical inference have not been very successful unless used to predict relative ET. Most of the same input requirements are needed as used for a simple water balance ET model. In many instances, it is necessary to develop some type of water balance model to estimate deep drainage. Thus it would appear the best use of soil moisture measurements in yield prediction would be to support a water balance-ET simulation.

Even though a model may perfectly simulate the soil moisture profile, the estimate of yield may not agree with measured yield. Yield modeling is not at the state of art to reflect perfectly crop response. In fact it may be several years before physiological process-models are developed and tested, and then, they may not be applicable to large area studies. The testing of these models may be extremely difficult because of the input data required. Current general physiological yield models are developed and tested with specific soil moisture models so that the inadequacies in the soil moisture model may be inadvertently incorporated in the yield and growth portion of the model. In addition, yield is not a single valued parameter but can be extremely variable over the field. Adequate sampling of large fields is seldom accomplished. Farmer yields can be misleading because of inaccurate and improper tallying in both acreage and production and unavoidable harvest losses.

The value of soil moisture measurements to current soil moisture and yield models cannot be fully assessed without further research. The value of these measurements is dependent upon the particular characteristics of the measurement itself (frequency, accuracy, depth of measurement, spatial averaging resolution) and the yield model. Soil moisture measurements would have no value in some regression models (e,g, Thompson); however, in models that simulate the transpiration, growth, and development of the crop on a daily basis, soil moisture measurements can have a significant effect. Thus it is possible that a yield model may have a very poor soil moisture model but may predict large area yields reasonably well. The models of the future will most probably be of the physiological type; therefore, soil moisture status will play an increasing role in yield modeling.

5.1 Use of Soil Surface Information

Moisture indices of the soil surface provide a limited feedback adjustment to most soil water balance models. Most dynamic/water balance models in current use provide four major water-depletion mechanisms: soil surface evaporation, transpiration, runoff, and drainage. The first few centimeters of surface soil is dominated by the surface evaporation mechanism, which has been defined in previous models by energy balance (using LAI, % cover or crop coefficients) and unsaturated upward flow equations (Saxton et al., 1974; Nimah and Hanks, 1973) or simplifications of these (Kanemasu 1979; Ritchie, 1972). The additional information feedback of sampled surface moisture would seem to offer little improvement to these directly. However, high frequency (daily) soil surface observations could be used to determine which soil surface evaporation equation--the constant rate (wet surface) or falling rate (dry) to use. Correlations of surface water contents (upper 15 cm) to total water content or water content in the dynamic root zone have been moderate ($R^2 = 0.60$) to poor ($R^2 = 0.0$) (Saxton-personal communications).

However, the indirect application of surface soil moisture updates may be useful when integrated into a total systems approach to profile water content and then yield. Surface water content, if monitored intensively (e.g. daily) could provide a primary input for systems models of:

(a) runoff problem areas ,
(b) water erosion problem sites ,
(c) spatial variability of rainfall and subsequent spatial variations in surface evaporation ,
(d) Watershed management,
(e) mandatory minimum tillage and ecofallow energy/soil conservation monitoring ,
(f) remote resolution of irrigation frequency and rates on larger systems (e.g. center pivots) ,
(g) remote resolution of irrigation frequency and rotation patterns in large surface irrigation projects such as in the Soviet Union and China ,
(h) pollution and saline seep reclamation,
(i) environmental impact data (strip mine seepage, etc.),
(j) planting date models ,
(k) trafficability and,
(l) thermal inertia .

These secondary uses for shallow soil moisture data are somewhat conjecture. However, spatial resolution of precipitation, irrigation frequency observations, and spatial evaporation patterns, could be of primary use to our soil moisture and yield models. Irrigation application monitoring would be of prime importance in world-wide application, where irrigations are seldom measured and recorded even less often.

Surface soil moisture could dramatically aid farm management (if utilized). Useful information on surface conditions aiding in pathogen development (e.g. rust, snowmold, winterkill, etc.) could provide an early warning for problems. Large area crop planning (seedbed preparation) might be aided. However, farmers are extremely independent and reluctant to accept new technologies unless benefits can be clearly shown.

6.0 Improvements to be Gained from Improvements in Precipitation Input Data

In those crop seasons when water is limiting, precipitation will have a strong influence on biomass and grain yield (see section 4.0). Thus models that include precipitation directly or a soil water balance will be subject to errors in yield estimates for particular fields of interest if precipitation (rain or snowfall) is extrapolated from the nearest observing station because both are spatially variable.

Procedures for estimating precipitation using meteorological satellite data, now underway by NOAA under AgRISTARS, can be expected to become operational eventually. The estimates should be available for approximately 1 km^2 cell. These estimates can be "blended" with existing ground measurement data to improve knowledge of both the amount and the spatial distribution of precipitation. The improved precipitation estimates should be available by the time crop growth models that merit the improved data are available.

7.0 Appropriate Scale for Yield Models

The size of an area used in working with models is quite important if the variables within that area are non-linearily related to the final calculation of a model (i.e. yield). If all variables were linearily related, then it would make no difference in the final calculations whether the input variables were averaged and the model run once for average data or whether the model was run for each consistant set of data and the final results averaged.

Unfortunately, for most biological systems, very few linear relationships have been found. This forces the use and testing of models to a unit small enough to allow sampling within a uniform area. It was the concensus of the committee that the unit of examination be a field. For use in this report, the term field is defined as a unit of land in which all variables used in the model are relatively uniform. The amount of uniformity will depend upon the sensitivity of the model to changes in that particular variable. This can be determined via sensitivity analysis. The calculations from the field can then be aggregated to any level by weighting the percentage of that unit within the area of interest.

8.0 Use of Remotely Sensed Data in Estimating Soil Moisture

Direct estimates of soil moisture from remote sensing techniques are limited to the reflected solar, emitted thermal and emitted microwave and backscattered microwave sensors. These techniques are primarily confined to surface moisture estimates for bare soil conditions. At sufficient vegetative cover so that plants dominate the signals, emitted thermal data best integrate plant response to soil water status _per se_. All wavelengths are affected by vegetation, canopy characteristics and/or surface roughness to a certain degree. Details on the theory and use of these techniques are given in a Soil Moisture Workshop Report (NASA Conference Publication 2073). That report concluded "Agrometeorological models supplemented by remote sensing inputs presently have the greatest potential for predicting soil moisture and soil moisture profile on a daily basis."

Many energy balance approaches estimate evapotranspiration by separating transpiration and evaporation. Other approaches use a crop coefficient curve which attempts to simulate the growth of a crop. These approaches require knowledge of the crop cover or leaf area index. It has been documented that green leaf area index can be estimated from the reflected radiation in the visible and near infrared wavelengths (Kanemasu, 1974; Wiegand _et al._, 1979; Tucker, 1978). For field by field monitoring of agricultural crops in the Great Plains, a spatial resolution similar to the current Landsat series is necessary. The desired temporal resolution for satellite acquisition is dependent upon the growth stage or plant development. During critical developmental stages of growth, greater sampling frequency may be required (e.g. every 3-5 days). The problem of cloud cover on satellite overpass dates is serious with the present Landsat repeat cycle (18 days). Only one to three usable satellite coverages per growing season are typical of more humid areas. The desired time of day for satellite observation is near solar noon especially if thermal band data are provided. This reduces evaporation problems associated with shadows and dew and emphasizes the physiological affect of water deficit. The tradeoff is the increased probability of cloudiness at midday over mid-morning.

Most plant response to soil moisture is described by plant available or extractable water at a given time relative to that of the fully filled root zone at the same time (0 to 100%). As plants undergo water deficit, transpiration is reduced and canopy or leaf temperatures tend to increase above ambient. Therefore, surface temperatures estimated by thermal infrared or microwave sensors may detect plant stress and/or infer available water content. A means of assessing the available water content for individual fields or agrophysical limits would be extremely useful.

When compared to visible and near infrared, relatively little work has been reported on the use of microwave wavelengths for monitoring vegetation mainly because microwave data registered with other wavelengths has not been available. Most microwave data have been related to near surface soil moisture (about 1.0 cm) and is of relatively minor interest in soil water balance modeling. However, it may prove extremely useful in runoff assessment and precipitation monitoring, both of which are involved in soil water budgets. It appears that microwave responds to green leaf area index (Ulaby-personal communication); therefore, it would have potential as a sensor on future earth resources satellites. Since microwave is basically insensitive to cloud conditions, it could supplement multispectral sensors (MSS, thematic mapper, etc.).

9.0 Recommendations

It would appear that improvements in yield modeling can come from improved soil water balance modeling. Improvements can be of immediate use in both regression-type and process-oriented models. However, consistent with the state of the art in crop modeling, relatively simple and empirical soil-water relationships are suggested in the associated soil water balance modeling effort.

Improvements in the soil water balance would result from:

1. improved procedures for estimating rooting depth as a function of time;
2. enlargement of the plant extractable water data base, and procedures for estimating it from existing soil survey or other data bases;
3. developing methods of estimating runoff and deep percolation;
4. improved precipitation amount estimates for any crop field or reporting area of interest--either by improved interpolation between observing stations or greater resolution such as the weather satellites provided;
5. improved growing season ET and/or relative ET/PET estimates by using earth resource satellite to estimate LAI, ground cover or a transpiring biomass; and
6. improved year-around estimates of the individual water balance terms, i.e. that include low ambient temperatures, frozen soil, intermittent snow cover, etc.

It is recommended that further studies be made to evaluate the usefulness of soil moisture information in yield models. Soil moisture measurements and the yield models should be evaluated together. In addition, an array of soil water balance models varying in complexity should be studied relative to predicting profile soil moisture for several soils and climates with existing data. Sensitivity analyses should be performed on the models to better understand how they respond to soil-water characteristics and input parameters. Data sets known to the committee are given in Appendix B.

It is also recommended that further studies be made to analyze what depth of the surface soil layer is required to be characterized in order to provide useful information in soil water balance modeling. Again, it is recommended that these studies use existing data.

It was noted that the state of the art in soil water balance modeling is ahead of physiological yield modeling. This is because we understand physical systems much better than physiological processes. Large improvements in yield modeling can be gained from improved knowledge of crop response (i.e. transpiration, photosynthesis, plant development, translocation and partitioning of assimilates) to environmental stress. As the relationships between yield and physiological processes become better defined, the greater will be the need for more accurate soil moisture profile information.

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Appendix A. Crop-weather - yield models.

A. Models Without a Soil Moisture Model.

Reference	Crop(s)	Input
Waggoner and Norvell (1979)	Corn, Alfalfa, Red Clover	N, Ph, K
Pochup *et al*. (1975)	Winter Wheat	P. T, HT
Runge and Odell (1958)	Corn	P, T, HT
(1960)	Soybean	
Thompson (1969a)	Corn	P, T, PP, HT
(1969b)	Wheat	
(1970)	Soybean	
Pitter (1977)	Wheat	P, T, PP, HT
Cate *et al*. (1979)	Wheat	P, T, PP, HT
Williams (1969)	Wheat	P, T, PP, SR

B. Models Including a Soil Moisture Model.

Reference	Crop(s)	Input
Yaron *et al*. (1973)	Wheat	P, T
Leeper *et al*. (1974a)	Corn	P,
(1974b)	Corn	P, T
Gross and Rust (1972)	Corn, Soybean	P, T
Bridge (1976)	Winter Wheat	P, T
Mapp *et al*. (1975)	Wheat, Corn, Sorghum	P, T, E
Hanks (1974)	Corn, Sorghum	P, E
Haun (1974)	Spring Wheat	P, T, PP
Feyerherm (1979)	Wheat	P, T, HT
SORGF (Mass and Arkin, 1978)	Sorghum	P, T, SR
Dale and Hodges (1975)	Corn	P, SR, LAI
Stewart *et al*. (1977)	Corn, Sorghum	P, T, E
LeDuc (1979)	Wheat	P, T, GDD, HT
Hill *et al*. (1979)	Soybean	P, T, SR
SIMCOT (McKinion *et al*., 1974)	Cotton	P, T, SR, E
Baker and Horrocks (1973)	Corn	P, T, PP, SR
Baier (1973)	Wheat	P, T, SR, PO

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Appendix A continued:

Reference	Crop(s)	Input
Lewin and Lomas (1974)	Wheat	P, T, HT, E
Strommen et al. (1979)	Wheat	P, T, HT, P-PET, ET/PET
SIMAIZ (Duncan, 1975)	Corn	P, T, SR, E, GDD
Rasmussen and Hanks (1978)	Spring Wheat	P, T, RG, E
Baker and Horrocks (1976)	Corn	P, T, SR, C, H, W
Kanemasu (1977, 1979)	Wheat	P, T, SR, LAI
EarthSat (1976)	Wheat	P, T, D, C, E, W, SR, NR, HT
Childs et al. (1977)	Corn	P, T, SR, H, W, LAI, GDD, PG
Slabbers, et al. (1979)	Alfalfa, Corn Sorghum	P, T, SR, H, W, C, DP, RS, PLP
Neghassi et al. (1975)	Wheat	P, T, E, SR, HT, W
Saxton and Bluhm (1979)	Corn	P, E, DP, HT, RG

Key to Abbreviations

C - cloudiness
D - dewpoint
DP - dates of planting
E - pan evaporation
ET - evapotranspiraiton
GDD- growing degree days
H - humidity
HT - historical yield trend data
K - potassium fertilizer
LAI- leaf area index
N - nitrogen fertilizer
NR - net radiation
P - precipitation (total growing season)
Ph - phosphorous fertilizer
PET- potential evapotranspiration
PLP- plant population
PO - phenological observations
PP - preseason precipitation
RG - root growth function
RS - row spacing
SR - solar radiation
T - temperature
W - wind travel (wind)

Appendix B. Existing data sets known to workshop memmbers. Data sets contain all the information necessary to test most of the yield models (some sets do not include soil hydraulic characteristics and/or leaf area index).

Investigator	Crop(s)	No. of years of data	Location(s)
Danielson	Soybean	2	1 state (CO)
Hanks	Corn	2	4 states
	Corn	3	1 state
	Winter Wheat	1	Utah
	Spring Wheat	2	1 state, 2 locations
	Spring Wheat	2	Australia
	Barley	2	1 state (Utah)
Heerman	Wheat		7 sites
Kanemasu	Wheat	3	Kansas
	Corn	3	Kansas
Keener	Corn and Soybeans	1	MO
Pruitt	Cotton	1	1 state (CA)
Rasmussen	Wheat	1	ID
Reetz	Corn and Soybeans	2	6 locations in IN
	Corn	7	IN
Saxton	Corn	14	IA
	Corn and Soybeans	3	MO
Wiegand	Wheat	2	TX
	Grain Sorghum	2	TX
Knievel	Corn	4	PA