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A Feasible Crop Yield Model for Worldwide International Food Production

by

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ABSTRACT. — This work addresses itself to the problem of deriving feasible computational methods for the determination of temporal and spatial agricultural distribution of productivity for potential application in international food production-allocation modeling. A solution has been sought through the creation of a crop-specific, crop-growth-stage-specific yield model (YIELD). The computer program is a compromise between area-specific regression models and expensive, complex energy and mass transfer models. The intra-seasonal soil moisture and evapotranspiration section of the model has been validated partially in previous publications, whereas the end-of season yield validation portion is briefly discussed in this summary paper of the model.

INTRODUCTION

Dramatic and unprecedented price increases on the world food market during the early 1970's have again emphasized the uncertainty and vulnerability of food supplies for this planet's increasing population. According to Linnemann et al. (1979), "The number of people that go hungry is larger today than ever before". This worldwide food problem has created recurrent anxieties about the world's ability to feed itself, and it has been a major concern of global models which all contain one or more agricultural sectors (Barney, 1980a, b; Herrera and Scolnik, 1976; Leontief et al., 1977; Meadows et al., 1972; Meadows et al., 1974; and Mesarovic and Pestel, 1976). In regard to climatic change, the popular media have widely publicized pessimistic views of the future, accompanied by conflicting advice given to the public and government agencies concerning policies and decision-making (Johnson, 1981). The disagreement among climatologists as to what might be the future fate of food production under fluctuating climatic scenarios has not eased confusion (National Defense University, 1980).

An analysis of future agricultural productivity has important social, economic, and political implications. Answers are needed as to the likely impact of climatic vagaries and fluctuations on food resources, international trade, food prices, and the search for

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areas best suited for growing certain crops in contrast to present cropping patterns. In 1976 the National Research Council (NRC) stated that "the national and international interests of the United States require that the impact of weather and climate fluctuations on domestic and world food supplies be examined so that rational responses can be planned for periods of stress" (NRC, 1976). All these concerns demand methodologies capable of evaluating the response of agricultural crops to climatic forces on a regional scale.

The soil-crop-atmosphere continuum is complex and is linked to many biological, physiological, physical, and chemical processes. Research has concentrated on developing the many methods and various models which exist for the calculation of crop yields. These models constitute a continuum of resolution, scope, explanation, and prediction. One end of the continuum is occupied by empirical regression models (Botkin, 1969; Raeuber and Engel, 1966; Scherer, 1978; and Thompson, 1975). In reference to the above, as Loomis and Ng (1978) stated so well: "the core of the problem is that the present state of the system integrates the past to determine future states". The dynamic nature of the problem however requires that models be dynamic (i.e., time-varying). It appears to be more desirable to go beyond statistical correlations which assume linear relationships between crop yield and environmental variables and which often are applicable only to the specific locations and time periods under which they were derived (Katz, 1977). At the other end of the continuum are deterministic crop growth models based upon the transfer of energy and mass within a multi-layered crop canopy, and which often include the partitioning of photosynthate within crop storage sites.

Essentially, a growth model exists for most of the world's major economic crops. The majority of these works represent temporal modeling with no attempts at spatial resolution for yields. Spatial photosynthesis or yield modeling on a regional scale has been attempted, for instance, by Baier et al. (1976), Band et al. (1981), Chang (1970), deWit (1967), FAO (1978), Feddes et al. (1978), Hayes (1980), Kassam (1977), Lieth (1974), Linnemann et al. (1979), Monteith (1972), Saugier et al. (1974), Szeicz (1975), Terjung et al. (1976) and Thomas (1975).

Thus, the major objective described herein was the development of a computer program capable of simulating and predicting seasonal crop yield for a number of major agricultural crops (spring wheat, winter wheat, spring rye, winter rye, spring barley, winter barley, grain corn, rice, early potato, late potato, and alfalfa). The result of this effort is the program YIELD. The program was to be relatively inexpensive even on regional or worldwide scales. The model was to have minimal data requirements, yet still allow flexibility in prescribing factors particular to a region or site which influence crop yield. YIELD has many cause and effect links and does not simply represent a series of linear relationships between selected environmental variables and crop yield.

The methodologies of Doorenbos and Kassam (1979), which quantify yield response to water applications through aggregate components and assess crop yield under irrigated or rainfed agriculture, form the basis of the yield model. However, appreciable modifications and additions were necessary to transform theory into a functioning computer program. The core of YIELD was formed by a previously developed soil moisture and evapotranspiration computer model WATER (Burt et al., 1980, 1981; Terjung et al., 1982) which has undergone further evolution since its inception. As was the case for WATER, YIELD is not "new" in adding to existing theory nor using new techniques, but it does offer a computerized feasible "package" of existing methods to be applied to worldwide or continental analyses and experiments. YIELD's contribution is considered mainly to be in that it is general and comprehensive in dealing with a rather large number of factors affecting yield response and in its ease of use and relatively low cost. We believe the model is a significant improvement over those currently used in global food modeling. Among the prominent physical crop production models for use of world food studies are the model of the agro-ecological zone project, AEZ (FAO, 1978), the model of international relations in agriculture, MOIRA (Linnemann et al., 1979), and the model of physical crop production, MOPCP (Buringh, 1980; CWFS, 1980). Virtually no attempts have been made to internally validate or compare these models with observed crop production. Also, YIELD is much more specific in regard to range of crops offered, soil type, and soil water budget considerations compared with these production models. A goal is eventually to combine YIELD with a socio-economic model of international food production, trade, and food allocation among nations. It is felt that a more physically-based approach instead of regression modeling to food production will improve the performance of global surplus/deficit food modeling efforts. Like any complex model, YIELD is not a finished product, but it is a constantly evolving model. It is potentially suitable for application to a single field and is currently feasible for regional and larger scale applications. Appropriate combinations of landscape scenarios were created for soil type, soil and irrigation water salinity, water table depth, management schemes, field size, etc., the rational being that for regional or worldwide use many such conditions are juxtaposed in any given area. Among the other factors also considered are wind régime, photoperiod, crop development stage, percolation losses, runoff, leaching requirements, salinity and fertilizer effects. The model can provide decision-making guidance in the choice of irrigated crops under different growing conditions. YIELD can also be used for the evaluation of crop yield under varying water supply schemes, and for the analysis assessments on which to base priorities for limited water allocation among crops. YIELD contains many default values which may be overridden by actual values reflecting conditions existing in a specific environment. Defaults present choices to a user from which the investigator picks the most representative value for a specific variable. Various (default) scenario schemes are utilized in YIELD to allow the user flexibility in selecting values representing various continuums, eg., good, adequate, or poor quality of irrigation water (IECW), or fine, medium, or coarse textured soils (ISOIL), etc.

This paper is primarily expository. The model is described in general terms only, together with the results of a series of validations comparing calculated estimates with field observations. A more technical and lengthy description of the model (including a listing of the program) is in preparation.

THE MODEL

BASIC APPROACH — Relationships between crop yield and water supply can be derived if crop water requirements-deficits and potential-actual yield data are simultaneously determined (Doorenbos and Kassam, 1979; Slabbers et al., 1979). Both evapotranspiration (ET) and yield are affected adversely by water stress. A much used ratio indentifying this stress is that of actual ET to maximum ET, ETa/ETm (relative ET deficit). Another useful index is the ratio of actual yield to potential yield, YA/YM (relative yield decrease). ETa/ETm is related to YA/YM via the yield response factor (KY). This latter empirical parameter varies with crop species, crop growth stage, and temporal sequencing. When water supply is optimum, YA = YM and ETa = ETm. Combining the above discussion more formally,

$$(1 - YA/YM) = KY(1 - ETa/ETm), \text{ or}$$
$$YA = YM\,(1 - KY\,(1 - ETa/ETm))$$
$$YA = YM - YM\,(KY\,(1 - ETa/ETm)) \qquad (1)$$

Doorenbos and Kassam (1979) have evaluated KY for many crops and climates, worldwide. These KY relationships apply to high producing varieties, well-adapted to their environment, growing in large fields under optimum cultivation practices, non-limited by fertilizer, herbicides, pesticides, trace minerals, etc. It was claimed that 80-85% of yield variation arising from water supply factors could be explained when using the method of equation (1). Obviously, few of the world's crops are grown under such favorable conditions. The production results of YIELD will serve as an indicator of the agricultural potential of an area or climate.

Yield response factors were determined for certain crop growth stages: establishment, vegetative, flowering, yield formation, and ripening (Doorenbos and Kassam, 1979; Utah Water Research Laboratory, 1977). Some KY's apply to a complete growing season when water stress is distributed more or less evenly over the season. Under intermittent drought, water stress from a previous stage is allowed to influence the KY's of the following growth stages. This simulates the ameliorating effect of previous stress or hardening of the crop for future stress. Consequently, the water sensitivity of a specific growth period (eg, flowering formation in grain corn) can be reduced by manipulation or management which causes an earlier deficit in the vegetative stage. Such pre-conditioning minimizes the effects of water stress at later stages (Utah Water Research Laboratory, 1977). In the program, the most appropriate KY and its associated growth stage-specific ET deficit is chosen and substituted into equation (1), thus solving for actual crop yield YA.

RELATIVE ET DEFICIT — The procedures leading to ETa and ETm have been discussed extensively in Burt et al. (1980, 1981), so only a schematic outline will be given here. Penman's equation was the basis for the soil water and ET section of the model. ET for the reference crop (termed CROP 1) derived by this equation was successively modified to include the effects of crop type, crop stage, and site factors. This included the influence of unusual climatic conditions, crop coefficients adjusting ET for specific growth stages, and soil moisture budget considerations. The sowing dates of the eleven crops can be estimated by latitude-dependent worldwide default options, or prescribed by the user. The determination of ET proceeds through a series of computing stages: CROP 1, 2, 3, 4, and 5. CROP 2 represents the adjustment of CROP 1 for wind régimes, radiation amounts, and mean daily maximum relative humidity different from the region (England) where the Penman equation was first determined. CROP 3 deals with the adjustment of CROP 2 by crop-specific, growth-stage-specific coefficients, characterizing the varying effect of growth stages on crop water use. CROP 4 adjusts CROP 3 for the "clothesline" and "oasis" effects because varying field sizes influence the crop microclimate. In this regard, especially in dry or semi-dry climates, irrigated fields could be surrounded by large dry tracts of land. A mass of air drifting over irrigated crops horizontally transfers sensible heat to the canopy during its passage. This represents the "clothesline" effect on the upwind edge of a field. The oasis effect occurs inside the irrigated field and sensible heat is vertically drawn from the air mass which has been modified previously by the convection originating from the barren, surrounding areas.

At this point, CROP 4 still assumes optimal water conditions (ETa = ETm). CROP 5 deals with a continuum of possible water stresses influencing crop-specific, growth-stage-specific ETa/ETm. A soil water budget is determined for each crop and season. This budget is a function of many variables, eg., growth-stage-specific ET, soil water storage, effective precipitation, groundwater contributions, variable root depths, percolation losses, irrigation frequency and amount, and leaching requirements. Each variable is evaluated at every time step ΔT (we used $\Delta T = 5$ days). The resulting water storage term is then used to determine the average soil water potential for the root zone, unique for each soil type scenario. This soil water potential value is then used to determine the ratio of actual to potential ET for each crop.

RELATIVE YIELD DECREASE — The core of the following procedure is taken from Doorenbos and Kassam (1979).

Maximum or potential yield. The maximum yield (YM) is the harvested yield of high-producing varieties under optimum growing conditions and actual farming practices of enlightened crop and water management. For alfalfa, grain corn, wheat, rye, and barley the "Wageningen Method" (YME) was adopted (Slabbers et al., 1979). For rice, the "Agro-Ecological Zone Method" (YMP) (Kassam, 1977) was utilized, whereas for potato the procedures of Feddes et al. (1978) (YM) were used. These methods are defined below.

The computation of the average gross dry matter production of a standard crop (AY) was determined by the method of deWit (1965). In FORTRAN notation (kg/ha day):

$$AY = AF * AYO + (1. - AF) * AYC \tag{2}$$

where

AYO, AYC = average gross dry matter production rates of a standard crop for a given location on overcast and clear days (kg/ha day);

AF average fraction of the daytime clouded sky, equal to (ARSE – 0.5 * ARS)/(0.8 * ARSE) — developed in deWit (1965);

ARSE average maximum photosynthetically active incoming shortwave radiation on clear days (ly/day);

ARS average observed incoming shortwave radiation (ly/day).

The maximum yield via the Wageningen Method becomes (kg/ha/ day)

$$YME = AY * K * CT * CH * G * (ACROP3/AGRADE) \tag{3}$$

where

K correction of general equation for a specific crop species (fraction);

CT temperature correction, a crop-specific function of mean seasonal air temperature (fraction) — accounts for respiration effects;

CH = correction for harvested portion, crop-specific (fraction);

G total growing season (days).

The correction for climate in regard to crop growth is related to the ratio of mean maximum ET (ETm or ACROP3) in mm/day and the vapor pressure deficit (AGRADE) in mb/day, resulting in ACROP3/AGRADE.

In the determination of the Agro-Ecological Zone Method (YMP), used for rice, the calculation of AY0 is identical with equation (2). If the standard production (for rice) is different from 20 kg/ha hr (assumed by the standard crop), YM is determined as a function of mean seasonal temperature. Using this, and when

$$YM > 20 \text{ kg/ha hr}, AY0 = AF * (0.8 + 0.01 * YM) * AY0 + (1. - AF) * (0.5 + 0.025 * YM) * AYC. \quad (4)$$

When YM < 20 kg/ha hr,

$$AY0 = AF * (0.5 + 0.025 * YM) * AYO + (1. - AF) * (0.05 * YM) * AYC. \quad (5)$$

Finally, the Agro-Ecological Zone Method results in (kg/ha day)

$$YMP = AY * CL * CN * CH * G \quad (6)$$

where

CL = correction for crop development over time and leaf area, a function of maximum leaf area index (LAI) during the middle of the total growing season (fraction);
CN = correction for net dry matter production (includes respiration), a function of mean seasonal temperatures (fraction).

For potato we adopted the procedure of Feddes et al. (1978) to derive YM:

$$YM = AY * PHF * ALFA * SC * BETAH * G \quad (7)$$

where

PHF = photorespiration factor (fraction) — for rationale see Feddes et al. (1978);
ALFA = limiting effect of air temperature on growth, a function of mean seasonal air temperatures (fraction);
SC = correction for fractional area of soil covered by plants (fraction);
BETAH = shoot/(shoot + root) parameter or harvested part (total plant ratio — fraction).

Actual Yield. The development to this point assumes that ETa = ETm. When ETa < ETm, crops vary in their response to water stress. This variable response is parameterized by the yield response factor KY in equation (1). This factor varies according to the sensitivity of a crop at a particular growth stage. Typically KY has highest values (most sensitive) during flowering and early yield formation, though this varies from crop to crop. Also, KY cannot be isolated from considerations such as fertilizer, planting density, crop protection, soil texture and structure, soil nutrients, salinity, etc.

YIELD also contains generalized default provisions for adjustment to less than optimal fertilizer applications of nitrogen, phosphorus, and potassium (NPK), and for the crop-specific sensitivity to saline soil conditions (SALINE). For the former we used information from Evans (1980), while the latter was adopted from Doorenbos and Kassam (1979). The effect of trace minerals (eg., zinc, copper, iron, molybdenum, etc.) was not modeled at this time.

PROGRAM CHARACTERISTICS — Figure 1 depicts a generalized flow chart for YIELD, combining the previously evolved WATER model with the yield portions of the computer program. The program is written in FORTRAN and used on the IBM 3033. The average cost of running one station for a growing season per crop type is

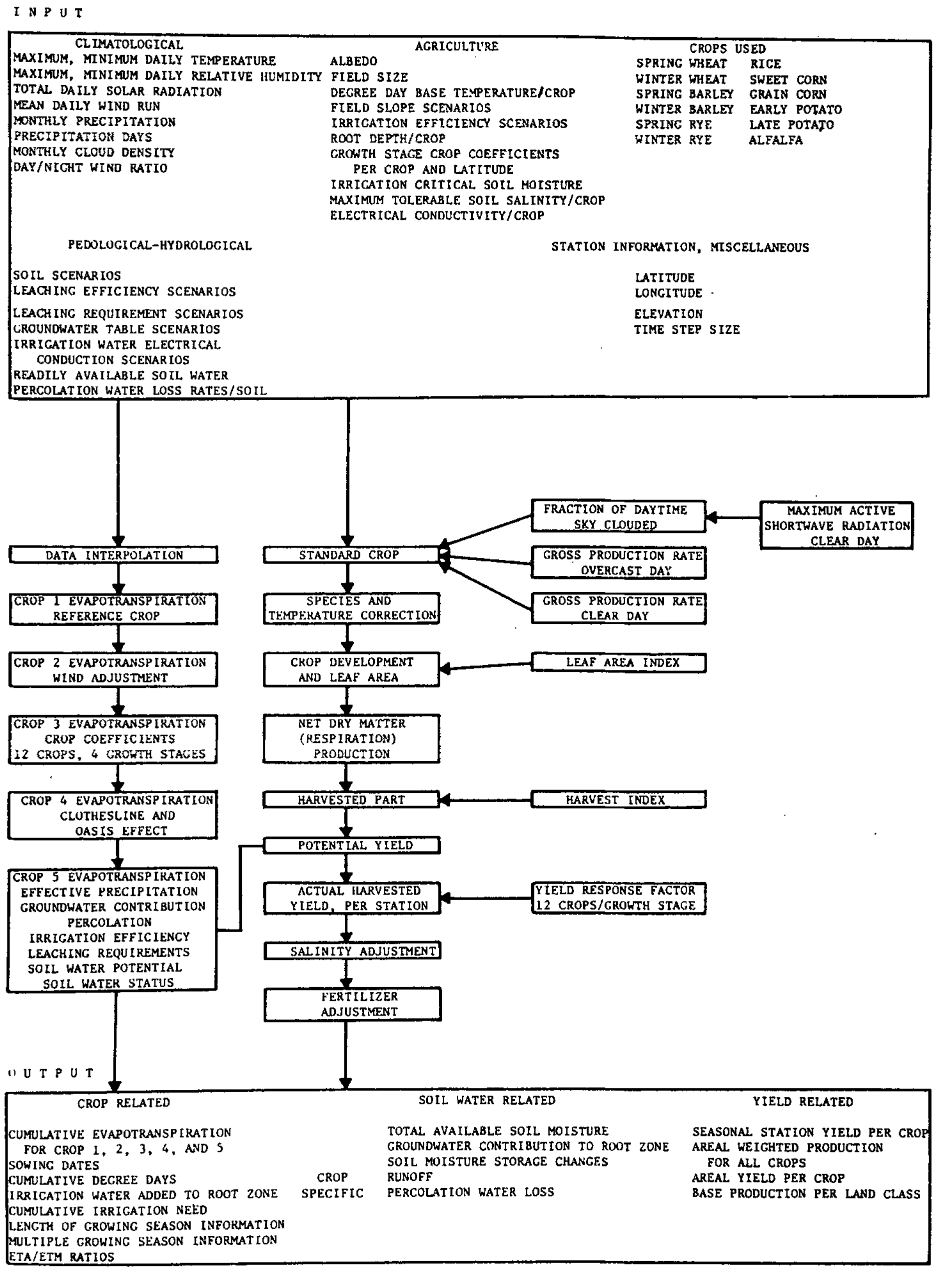

Fig. 1. Generalized flow chart of the combined ET and yield calculations of the model YIELD.

about $ 0.30. A program listing, accompanied by sample input and output, is available in a companion paper (in preparation).

After declaration statements, YIELD begins by establishing values for constants (eg., time step size and scenario options — Table 1). The outer-most loop is entered which controls the number of stations to be studied; reading one year's climatic input data. After the interpolation of these inputs, the sowing dates are either determined by default or prescribed for each crop, and stored in a vector. Upon the prescription or determination (default) of an initial soil moisture budget, the crop loop is entered. The default sowing date is examined to be sure the crop is viable in the particular environment. If the crop can be grown, the amount of stored soil moisture is retrieved from the initial soil moisture budget, and converted to moisture present in the root zone. Alternatively, the user can skip this default procedure and assign a known or observed initial soil moisture content at the beginning or the growing season.

Next, the time loop begins with the computations of CROP 1, 2, 3, 4, and 5. The variable plant response to water stress is introduced in the portion of the program dealing with CROP 5. In the model, the ratio of actual ETa to the reference crop ET (COEFF) approaches a value of zero as the wilting point is reached. The ability to

Table 1. Scenario options available in YIELD

Scenario	Code 1	Code 2	Code 3
ISOIL*	Sandy coarse texture	Clay fine texture	Loam medium texture
(ASOILW)	(60. mm/m)	200. mm/m)	(140. mm/m)
IHECT	0.1 hectare	1.0 hectare	1000 hectares
ILEFF	1.0	0.5	0.7
ILR	ordinary surface irrigation methods	drip, high frequency sprinklers	
ISLOPE	flat	sloping (> 15 deg)	
IEFFIC	0.50	0.65	0.75
IGWDEP	8.0 m	2.0 m	4.0 m
IECW	3.0 mmhos/cm	1.83 mmhos/cm	0.62 mmhos/cm
CLIMAT	leaching unnecessary	leaching may be necessary	

	Code			
RATIO	1	2	3	4
day/night wind ratio (RAT)	4:1	3:1	1:1	2:1

* ISOIL = soil texture, IHECT = field size, ILEFF = leaching efficiency, ILR = irrigation method, ISLOPE = surface slope, IEFFIC = irrigation project efficiency, IGWDEP = groundwater depth, IECW = irrigation water quality, CLIMAT = climate type, ASOILW = total available soil water, RATIO = day/night wind code, RAT = daytime wind velocity/nighttime wind velocity.

withstand water stress is highly variable among crops. This is accounted for on a crop-specific (and growth-stage-specific) basis. Variables simulated in the soil water budget include crop-specific, growth-stage-specific ET, previous soil water storage, effective precipitation, groundwater contributions, irrigation needs, and leaching requirements. Regarding the last variable (ILEFF in Table 1), it refers to the efficiency with which the extra water added for leaching out salts accomplishes its desired task. The leaching requirement is the minimum amount of water in excess of crop consumptive use which is necessary to be drained through the root zone to control soil salinity at a given specific level. Leaching efficiency has been shown to vary with soil type, particularly with the internal drainage properties of the soil and field, soil management practices, irrigation method used, and soil moisture content at time of leaching. Related to leaching considerations, the user can choose from three values representing good, adequate, or poor quality of irrigation water in regard to salt content (IECW in Table 1). (These values, expressed in units of electrical conductivity in millimhos/cm (mmhos/cm) are averages from a variety of agricultural crops as taken from the literature (eg., Ayers and Westcot (1976). Each of the variables are evaluated per time step (DT) along with a resultant soil water storage (STOR) and soil water potential (PSI).

Finally, the appropriate yield response factor is assigned. The determination of KY entails seasonal and intra-seasonal searches for the changes in growth-stage-specific KY and the concurrent ETa/ETm ratios. Algorithms are solved in a series of comparisons resulting in the final choice of KY (highest value). In addition to the main program, YIELD contains 26 subroutines and 3 function subprograms. The entire program currently consists of about 2800 lines. Figure 2 gives an example of typical output from the computer program for the end of a growing season.

MODEL VALIDATION

INTRODUCTION — Any report on a model validation should be preceded by a discussion of the validation criteria which, in turn, are determined by the use to which the model is to be put. At this point of its evolution, YIELD is seen to be applied primarily geographically, on a regional, national, continental, or worldwide basis. The output of the model would become the input to socioeconomic global models of international agricultural production, trade, and food allocation. As additional, suitable validation data become available in the future, YIELD could evolve to the point that the output will become sufficiently accurate to be used on a field-to-field basis. Currently, such accuracy is achieved by empirical, regression-type models designed for specific areas and time periods. Unfortunately, such simple models lack generality and a meaningful cause and effect structure (see above).

Doorenbos and Pruitt (1977) have previously validated the reference crop ET (CROP 1, Penman-based) on a worldwide basis. Specific validations for CROP 3, 4 and, in some cases for CROP 5, were conducted by Todhunter (1981), Burt et al. (1980, 1981), and Utah Water Resources Laboratory (1977). Most of these tests utilized lysimeter-based or neutron probe and gravimetric data.

With respect to the actual harvestable yield (YA), a search of the literature revealed a paucity of useful papers with reliable procedures and documentations. Over 100 data questionnaires were mailed worldwide to experimental agronomists and government agencies in a quest for validation data. Unfortunately, many of the data sets obtained were incomplete in one or several vital aspects.

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*****************************************************************************************************
*                                                                                                   *
* CLIMATE DATA PER TIME STEP-----DT NUMBER 36                                                       *
*                                                                                                   *
=====================================================================================================
*                                                                                                   *
*   DAY:   226.     TMAX:   31.83  TMIN:    13.93  TMEAN:    22.88                                  *
* (CELCIUS)       (CELCIUS)       (CELCIUS)       (CELCIUS)                                         *
*                                                                                                   *
*   V24:      3.58  RHMAX:  78.98  RHMIN:  35.84  RHMEAN:    0.57                                   *
*  (MI/HR)          (%)            (%)            (FRACTION)                                        *
*                                                                                                   *
*   QAQ:   620.8    N:        0.13  PRECP:    2.5   DDAYS: 2587.07                                  *
* (LY/DAY)        (FRACTION)      (MM/MON)                                                          *
*                                                                                                   *
=====================================================================================================
*                                                                                                   *
* LEVELS OF CROP EVAPOTRANSPIRATION                                                                 *
*                                                                                                   *
=====================================================================================================
*                                                                                                   *
*   CROP1:    7.38  CROP2:    9.00  CROP3:    5.63  CROP4:    5.63  CROP5:    5.63                  *
*   (MM)            (MM)            (MM)            (MM)            (MM)                            *
*                                                                                                   *
*   SUMC1:1123.1    SUMC2:1327.5    SUMC3:1131.6    SUMC4:1131.6    SUMC5:1131.6                    *
*   (MM)            (MM)            (MM)            (MM)            (MM)                            *
*                                                                                                   *
=====================================================================================================
*                                                                                                   *
* SOIL WATER BUDGET CHARACTERISTICS                                                                 *
*                                                                                                   *
=====================================================================================================
*                                                                                                   *
*   ROOTD:    1.35  STOR1:  136.59 CAP:     189.0   PREVST:     0.0 EFFPRE:    1.8                  *
*   (M)             (MM)           (MM)             (MM)            (MM)                            *
*   GW:  0.00  IRRIG:   0.00  IRRACC:      512.4   IRRAPL:  683.2 WATCAP:  52.4                     *
*   (MM)            (MM)           (MM)             (MM)            (MM)                            *
*                                                                                                   *
*   SMCRIT: 60.40   P:        0.569 PSI1:      0.48 WATER:      1.00 STOR2:  136.59 PSI2:  0.48     *
*   (MM/M)          (FRACTION)     (BARS)           (FRACTION)       (MM)           (BARS)          *
*   DAYS:   10.     RUNOFF:   0.00 RNOFAC: 858.80 PERC:       0.00  PERCAC: 346.42                  *
*   (MM)            (MM)                            (MM)             (MM)                           *
*                                                                                                   *
*****************************************************************************************************
G R A I N   C O R N   H A R V E S T  SACRAMENTO  CALIF
GROWING SEASON LENGTH:185. DAYS--MEAN SEASONAL TAIR: 18.11 C--TEMPERATURE CORRECTION FACTOR:0.44

KY, CHECKY, CH:     0.000    1.000  0.4500
ARSE,AYO,AYC,ARS,AGRADE:    340.88  222.25  426.67  577.67    8.25
   ACROP3,ACROP5,AF,AYO:    6.12    6.12    0.19 387.66
YA1,YA2,YA3,YA4: 20162.13 20162.13 20162.13 20162.13 RATAP1,RATAP2,RATAP3,RATAP4: 1.00 1.00 1.00 1.00
CKY12,CKY3,CKY4A,CKY4B,KY:     1.0000    1.0000    1.0000    1.0000    0.0000

                        YME:  20162. YA1:  20162. RATAP1:1.00 SUMC3:1131.6
                        SUMC5:1131.6 DDAYS: 2701. SUMEP: 152.6 SPREST:1552.9
                        IRRACC: 512.4 IRRAPL: 683.2 EY:  1.78 EFFPHY:     0.91
                        EFFMGT: 0.84
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Fig. 2. Example of end-of-season output of YIELD for grain corn (Sacramento, California). The actual output, repeated for each time step (DT) amounts to many pages per season, only the last DT and the harvest summary are shown.

RESULTS — YIELD's basic methodology has been validated previously both in general applicability and specifically for corn and alfalfa (Slabbers et al. 1979). A major data source for the validation of grain corn came from the Utah Water Resources Laboratory (1977). This work was carried out by four universities with experimental sites in Yuma, Arizona; Davis, California; Fort Collins, Colorado; and Logan, Utah. Field experiments were carried out at each of the sites during 1974 and 1975. At all four sites the same basic philosophy and experimental techniques were followed, producing a comparable set of data. Figure 3A shows the comparison of observed versus calculated yield for grain corn from these four sites. The graph presents the results from a range of water stress conditions. The average observation equals 6692 kg/ha, whereas the average calculation equals 6889 kg/ha. The root mean square error of estimate (RMSE) is 1344 kg/ha (Table 2).

Another source of seasonal data was the Utah State University at Logan for the 1979 spring wheat and spring barley growing season (Hanks, Hubbard, Wenda, and Win-

Table 2. Yield amounts and root mean square error of estimate (RMSE).

	Amount*		RMSE
Crop	Average Observed	Average Calculated	Yield (YA)
Grain Corn	6692	6889	1344
Rice	8936	9346	1391
Spring Wheat	3255	3791	930
Alfalfa	1755	1694	443
Spring Barley	4217	6017	2227

* Amounts in kg/ha.

ward, personal communication, 1981). The experimental plots were handled similarly to the above four-university study, the fields being set up as a continuous variable design (for details of the field experiment, see Wenda, 1979). Figures 3B and 3C show the results of the comparison between observations and model simulations. Again, the values contain both water stress and non-stress conditions. The average observations for spring wheat are 3255 kg/ha and the average calculated values are 3791 kg/ha, with an RMSE of 930 kg/ha. The analogous values for spring barley are 4217 kg/ha and 6017 kg/ha. This latter comparison is by far the poorest of the validation set, demonstrating an apparent consistent overprediction by YIELD, although this conclusion is tentative since it is based upon only one validation set. Also, since the model's main purpose is the spatial determination of potential yields on a worldwide basis, the relative unimportance of spring barley as a major food source makes this discrepancy of diminished a nature.

A set of rice data was provided by the University of California at Davis (Hill, personal communication, 1981). The eleven stations supplied contained less detail in environmental input needed to recreate the specific time and site conditions. The observations were conducted in 1979-80 by the Rice Experiment Station, California Co-operative Rice Research Foundation (Biggs, CA) and the Demeter Corporation (Sacramento, CA). The observations were from seven different counties (Figure 3D). The average observed yield is 8936 kg/ha in contrast to the average calculated yield of 9346 kg/ha, with a RMSE of 1391 kg/ha.

For alfalfa a set of data was received from the Agricultural Research Institute at Nicosia, Cyprus (Krentos, personal communication, 1981; Metochis, 1981). Unfortunately, no solar radiation records were available for the test period (1976-78). Radiation was estimated via the Savino-Angstrom equation (using the ratio of sunshine hours to daylight hours and solar radiation received on top of the atmosphere). Also, an average value for the harvest index (CH) had to be assumed to which equation (3) is strongly sensitive. CH was not specified in many validation data sets. The calculated results are reasonable and within the inherent accuracy of the model methods when optimum water is applied to the crop. The average observed value equals 1755 kg/ha versus 1694 kg/ha for the average calculated result (RMSE = 443 kg/ha). For suboptimal water supply conditions, results were unsatisfactory compared to observations (after the first 2 or 3 cuts of the season), at least with this one set of data. This could be an indication of model weakness, particularly in regard to the yield response factor,

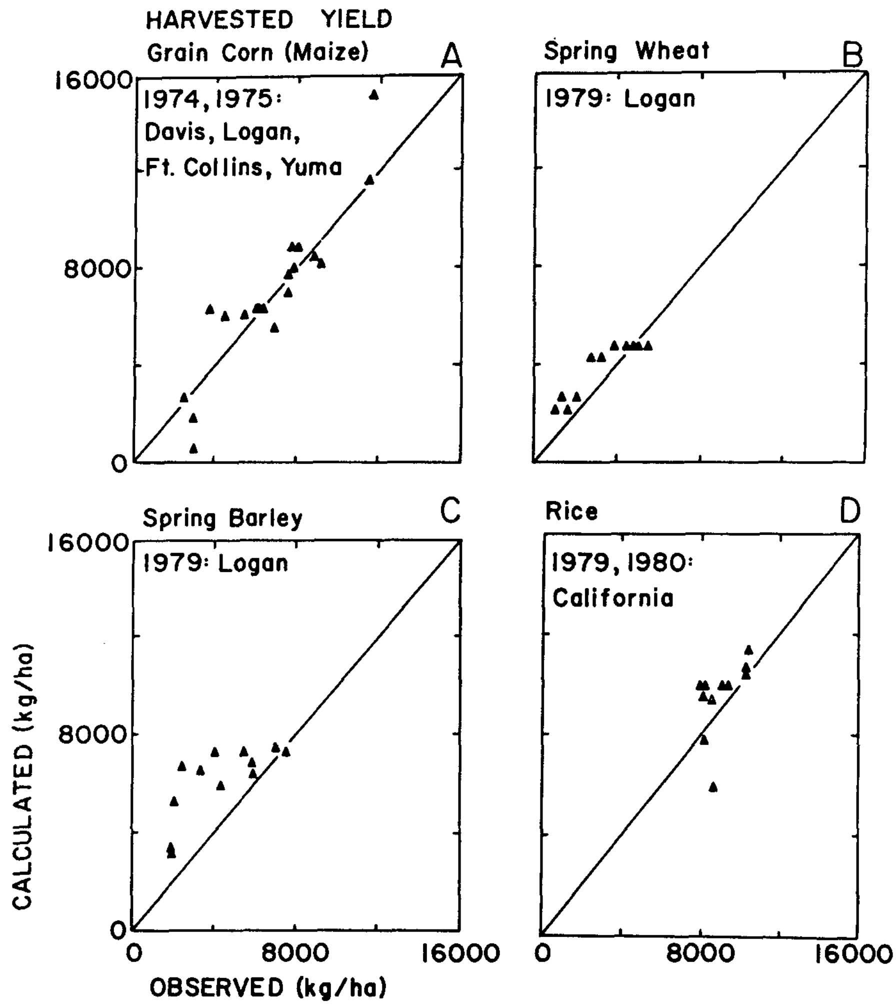

Fig. 3. A. Comparison of observed yields of grain corn versus calculated yields by YIELD for the 1974 and 1975 growing season at Davis, California, Logan, Utah, Ft. Collins, Colorado, and Yuma, Arizona (kg/ha). Ten of the data points represent non-stress water conditions for 1974 (Davis, Logan, Ft. Collins, and Yuma) and 1975 (Davis, Logan, Ft. Collins). The remaining nine data points depict stressful water conditions for 1974 (Logan, Ft. Collins, and Yuma).
B. Comparison of observed yields of spring wheat versus calculated yields by YIELD for the 1979 growing season at Logan, Utah (kg/ha). The data points represent both stress and non-stress water conditions.
C. Comparison of observed yields of spring barley versus calculated yields by YIELD for the 1979 growing season at Logan, Utah (kg/ha). The data points represent both stress and non-stress water conditions.
D. Comparison of observed yields of rice versus calculated yields by the model YIELD for 1979-80 in California (kg/ha). The 11 stations were located in Merced, Sutter, San Joaquin, Butte, Glenn, Yolo, and Sacramento Counties.

Table 3. Average seasonal yield comparisons for early potato for non-experimental field data (kg/ha) — 1967-69 (Macfarland, 1970).

State	Location Used for Model	State Average Reported	Model Prediction
Maine	Caribou	26077	27166
New York	Rochester	27422	25849
New Jersey	Philadelphia	28580	24653
Pennsylvania	Pittsburgh	24844	24969
Michigan	Detroit	23836	26488
Wisconsin	Madison	25778	25442
Minnesota	Minneapolis	16177	24321
North Dakota	Devil's Lake	15093	28489
Virginia	Norfolk	14720	30848
North Carolina	Wilmington	15430	25704
Florida	Jacksonville	17709	18979
Idaho	Pocatello	23462	31608
Colorado	Pueblo	26824	30740
Washington	Walla Walla	42254	29083
Oregon	Portland	29739	29072
California	Sacramento	34894	26678

deficiencies in the observational data, the sensitivity of the model to assumptions because of inadequate environmental input, or combinations of all.

We were unable to obtain a reliable set of potato data for a rigorous yield validation. Consequently, only a limited comparison between reported statewide yields of the primary producing states in the U.S. was attempted (Table 3). The predicted results represent totals for the nearest (available to us) locations to the actual growing areas. Also our selected stations utilized long-term climatic data, whereas the state potato yields represented the average of three specific years (Macfarland, 1970). Thus the results from YIELD do not match specific years and stations. The model run used sufficient fertilizer (NPK = 1) and irrigation applications (H2OAPL = 1), conditions not necessarily obtained in the statewide data. Commercial potato production is found on a wide range of soil types. Either fertile soils or heavy fertilization is necessary to obtain the high yields calculated by the model for this comparison. For instance, areas such as Maine, New York, Pennsylvania, Florida, and California boast the highest percentage of fertilized acreage (Martin and Leonard, 1967). In these regions, YIELD's predictions were among the best (Table 3). On the other hand, in areas of lesser fertilized acreage (e.g., Minnesota, North Dakota, and Idaho) our predictions exceeded considerably the reported values.

Additionally, this comparison suffers from assumptions concerning field size, water salinity, soil conditions, irrigation efficiency and frequency, agronomic practices, varietal differences, diseases, insects, weeds, etc. For instance, potatoes are harmed by even mildly stressful water situations. Despite these problems, and deferring a rigorous validation to a time when and if such data become available, it appears that the potato predictions of YIELD are reasonable.

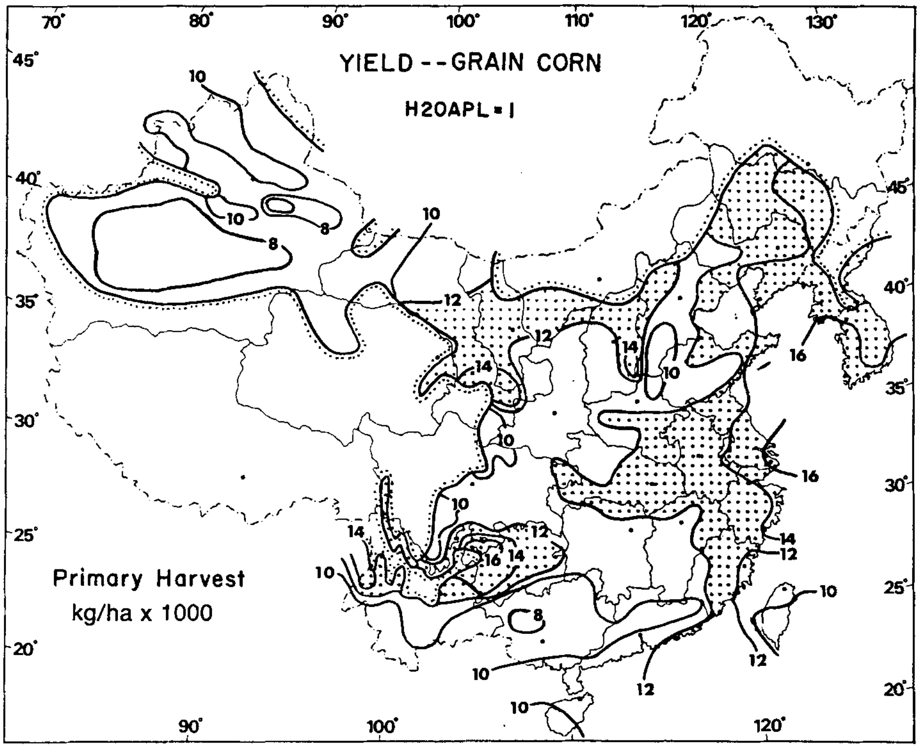

Fig. 4. Actual yield (YA) of grain corn for China and Korea for the primary (first) growing season or harvest (kg/ha * 1000). The fraction of irrigation water applied to the root zone H2OAPL = 1, with the minimum allowable number of days between irrigations being NDAYS = 5. The isoline interval is 2000 kg/ha. The solid curves paralleled by dots identify the approximate areas where YIELD estimated commercial grain corn production was not feasible because of unfavorable climatic (too cold) conditions. The isolated dots on the map identify provincial capitals of China. The solid lines are provincial boundaries.

In summary, considering the above stated problems in obtaining sufficient, accurate and fully documented seasonal data sets, reasonable and consistent intra-seasonal (see Burt et al., 1980, 1981; Todhunter, 1981) and end-of-season predictions are obtained. Considering YIELD's intended purpose of large areal simulations of crop yields (including a means of investigating environmental effects on crop yields), the results are encouraging. Obviously, the model will continue to evolve, partially as a result of future tests versus observed data, if and when they become available.

AN EXAMPLE OF THE REGIONAL APPLICATION OF THE MODEL

In order to demonstrate the regional capability of YIELD, the model was run for the grain corn growing seasons of China and Korea. The seasonal climatic input of 241 stations was utilized (Central Meteorological Bureau, 1978; U.S. Department of Commerce, 1962; Meteorological Office, 1966). The additional environmental input (see Table 1) was obtained by consulting the FAO soil maps (FAO/UNESCO, 1974). We conducted two experiments, one under fully irrigated conditions (the fraction of irrigation water applied to the root zone H2OAPL = 1; the minimum allowable number of days between irrigations NDAYS = 5) and one under rainfed conditions only (H2OAPL = 0). The approximate cost in computer time for each experiment was $ 70. The complete results of this study are presented elsewhere (in preparation).

As an example, we show only the resultant actual yield of grain corn under fully irrigated and fertilized conditions for the first harvest (Figure 4). Three major potential production centers become apparent (eg., see isolines > 1200 kg/ha): (1) eastern China from the Yangtze river northwards and Korea, (2) the Kweichou Province area, and (3) northcentral China, primarily at the upper reaches of the Huang Ho river. Because southern China has the potential of several growing seasons (2-3 per year), Figure 4 might be misleading since only the first harvest is shown. For the annual case, southern and southeastern China excel in yields (approaching a potential of 20,000 kg/ha on a yearly basis).

The companion map of the first harvest for H2OAPL = 0 for rainfed agriculture (not shown) is quite different in the drier north and northwestern parts of China. The ratio YA/YME (actual/potential yield) ranges from unity in the south, southeast and east, through about 0.4 in the upper Huang Ho river regions, and to zero in the Tarim Basin and Dzungaria. For the fully irrigated first harvest, ET ranges from 400 mm (southern China) to over 800 mm in the drier interior, whereas the applied irrigation to the root zone (supplemented by effective precipitation) is nil in large areas of the south and east, while reaching over 1,000 mm in the interior.

We define "management efficiency" (EFFMGT) as equal to the amount of harvested yield produced by the crop per unit of water added to the root zone (kg/m^3). The denominator includes seasonal sums of effective precipitation, soil moisture accumulated from before the growing season, and the actual applied irrigation (adjusted for leaching requirements and management efficiency of water application). EFFMGT (H2OAPL = 1, first harvest) varies from low values of about 0.6 in the dry interior to considerably greater than 1.5 in the southern and eastern moist coastal areas. This would indicate a rather low feasibility of introducing irrigated grain corn to the interior, western regions of China.

In summary, this brief depiction of the application of YIELD to a large region of the world can be expository only. The detailed explanation of the isolines appearing in Figure 4 ultimately can be accomplished only by the examination of each of the major components of the presented equations, as they vary spatially and temporally (in preparation). Because of the parametric nature of the model, such explanations are deemed more elucidative compared with the spatial results of empirical regression models, though aiming at the same objective.

FINAL REMARKS

The goal of this research is the construction of a worldwide yield model for the major commercial agricultural food crops. It is our intent to retain as many physically-based features in this parametric model as possible (contrasted to regression modeling) and yet be feasible in terms of required computer resources for the spatial application of this model on a worldwide or continental scale. YIELD was formulated in response to a worsening global food supply situation in relation to climatic fluctuations. It is hoped that the model will eventually be linked to a system of international agricultural production, trade and food allocation modeling. At this point, YIELD cannot simulate policy, but it can provide, for instance, a tool in the examination of alternatives in decision-making under different climatic scenarios, instead of political innuendo.

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